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MANUFACTURING METHODS
FOR
AN EXTREMELY LONG LIFE TUNABLE ICEM® MAGNETRON

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Subsidiary of Varian Associates
Union, New Jersey

TECHNICAL REPORT AMFL-TR-68-168

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Air Force Materials Laboratory
Air Force Systems Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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FOREWORD

This final technical report covers the work performed under Contract AF 33(615)-3183 from 1 July 1965 to 1 April 1968. This contract with S-F-D laboratories, inc., Union, New Jersey, was initiated under Manufacturing Methods Project 8-283, "Development of Manufacturing Methods for Producing Long Life X-band ICEM® Magnetrons." It was accomplished under the technical direction of Captain William Horsfield of the Electronics Branch (MATE), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The work was performed under the direction of Dr. G. K. Farney, Technical Director of S-F-D laboratories. W. R. Lundberg, Manager of Product Development and Manufacturing, was responsible for the performance of the contract. F. L. McClung, Manager of Product Development, was responsible for technical coordination of the contract; A. Cook, Senior Electrical Engineer, was the principal contributor to the electrical design and evaluation of this program. He was assisted by P. Bahr, Electrical Engineer. M. Liscio, Design Engineer, was the principal contributor to the mechanical design.

This document has been assigned S-F-D laboratories report number 67-F.

The report was submitted by the authors in June 1968.

This technical report has been reviewed and is approved.

Jules I. Wittebort

JULES I. WITTEBORT
Chief, Electronics Branch
Manufacturing Technology Division

ABSTRACT

This report describes the work performed and the results obtained on a program to improve the operational performance of a basic ICEM coaxial magnetron. In addition, manufacturing methods were to be established which would allow volume manufacture of the device at reasonable costs.

The fundamental performance requirements were the generation of 500 kw peak power minimum at X-band tunable over the band from 8.6 GHz to 9.6 GHz. Of particular importance was the goal of a life capability exceeding 10,000 hours.

The starting point of this program was the SFD-328 ICEM coaxial magnetron, which had the status of a laboratory test vehicle. However, this device had demonstrated performance which confirmed that the objectives of this program were realistic and achievable.

The program which utilized the progress phases of the basic manufacturing methods approach, consisted of two elements:

1. Electrical design refinement, formulation of manufacturing methods, and production demonstration of the design's reproducibility and manufacturing processes;
2. Demonstration of life capability.

The final device resulting from the performance of this program is discussed, including advantages and limitations.

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1.0 GENERAL PURPOSE AND OBJECTIVES OF THE PROGRAM

In recent years, an overriding requirement in new systems has been for improved reliability and increased life for all electronic components. Admittedly, one of the major limiting factors in achieving this objective has been the magnetron oscillator. There has been, on the other hand, some significant contribution toward this end with the advent of new approaches to magnetron design, such as the CEM® and ICEM® coaxial magnetrons.

The ICEM coaxial magnetron, which was originally proved feasible and developed into a practical, operational device at Ka-band under the direction of the Air Force, should now be extended to other frequency bands. X-band was the logical frequency range because of its high utilization.

The initial performance requirements were such that the tube should generate 500 kw peak power minimum at X-band, tunable over the band from 8.6 GHz to 9.6 GHz. Of particular importance was the achievement of a life capability exceeding 10,000 hours.

Thus, the primary purpose of this program was to make available an advanced device with RELIABILITY and LIFE as the major considerations along with a minimum manufacturing cost consistent with these considerations.

1.1 Factors Affecting Magnetron Life and Tube Design Philosophy

Fundamental to extremely long life consideration in magnetrons is the design of the cathode, which is basically the only active part of the magnetron. The life may be extended by proper choice of emitter, its operating temperature, and the current density demands placed upon it. Once a cathode type is selected, its operating temperature for optimum life is known. The design of the cathode is then directed toward maintaining this temperature as closely as possible. The selection of the proper heater reduction schedule, along with the mechanical design of the cathode, can insure that this cathode temperature is held within the necessary tolerances.

The cathode loading in terms of current per unit area can only be reduced at a given current level by increasing the cathode surface area. In the conventional magnetron, the cathode area is limited by interaction requirements. The diameter of the cathode is related to the anode diameter, which, in turn, is related to operating voltage. To increase the anode diameter in a conventional tube at a given operating voltage, the number of resonators must also be increased. The number of resonators determines the amount of frequency separation between the desired π mode and the competing modes on the circuit. Too small a separation in mode frequency will result in significant mode instability difficulties during pulsed operation. Thus, there is usually little flexibility for increasing the cathode diameter. This leaves only the length of the cathode available to increase surface area. The choice again is limited, but for other reasons. An increase in cathode height must be accompanied by an equal increase in anode height. Any increase in anode height will require a corresponding increase in the gap length between the pole pieces. This, in turn, will increase the magnet weight proportional to the square of the gap length increase, resulting in a much heavier, larger tube. For some systems, this might not be a major limitation; however, the physics of interaction again restrict anode height for reasons much more basic than weight and size. Normal strapped magnetrons are susceptible to axial mode problems when the vane height is increased more than $0.3\ \lambda$. At X-band, this would limit the circuit height to approximately 0.370" which is quite close to the vane height used in existing high power X-band magnetrons. The use of a rising sun anode structure would permit larger circuit heights, but introducing tunability in this type of design, together with the magnet weight increase required, makes any substantial increase in cathode area by increasing axial length impractical.

The following table depicts various critical cathode design characteristics for initial redesign version of the SFD-328 and for two widely used conventional magnetrons.

TABLE I

COMPARISON OF X-BAND ICEM COAXIAL MAGNETRON
WITH MAGNETRON TYPES 7008 AND 6249

	7008 Magnetron	6249 Magnetron	X-band ICEM Coaxial Magnetron
Peak power (min) - kw	200	200	500
Average power (min) - w	200	200	500
Peak voltage - kv	22	28	28
Peak current - amps	27.5	25	50
Cathode area - cm^2	1.12	1.82	13
Cathode current density - amps/cm^2	25	13.7	3.8
Anode vane area - cm^2	0.84	1.4	7.0
Peak power dissipated in anode bore area - kw/cm^2	480	240	120

While developing two and one-half times the output power of the conventional magnetrons, the ICEM magnetron cathode current density is less than one-quarter that required by the conventional tubes. Utilizing the ICEM coaxial magnetron principle, we can amply fulfill the primary conditions for long tube life.

Additional factors must be considered to produce long magnetron life. One of these factors concerns the power dissipation density on the anode circuit. In the conversion of dc input power into RF power on the circuit, some unconverted input power must be absorbed on the circuit. The density of this unconverted power in terms of kilowatts per square centimeter is instrumental in producing transient temperature variations on the circuit surface areas upon which this power is dissipated. The temperature rise at the surface of the vanes after the end of the first pulse may be shown to be equal to

$$T = \frac{2\phi c \sqrt{k t_o}}{K \sqrt{\pi}} \qquad (1)$$

where ϕ = power dissipated per unit area on the vane tip

k = thermal diffusivity = $K/\rho c$

K = thermal conductivity

c = specific heat

ρ = density of anode material

t_o = pulse duration

It may be seen that expected transient temperature rise will be directly proportional to the density of power dissipation. Since the circuits used for anodes are copper in both the ICEM coaxial magnetron and in conventional tubes, it is possible to compare transient effects under identical pulse conditions. Reference to Table I shows that power densities on the ICEM coaxial magnetron during operation (at two and one-half times the output power of the conventional tubes) are a maximum of one-half that experienced on the conventional tube anode circuit. This will produce transient temperature rises of one-half those encountered in the conventional tubes. As a result, no degradation in tube performance with life may be expected as a result of erosion of the anode vane circuit.

Other considerations involved in producing a long-lived magnetron relate to all vacuum tubes. In a well-evacuated tube, a large number of gas molecules are still present, but they do not seriously interfere with the movement of electrons at this level of population. At higher pressures, a sufficient number of gas ions are produced by electron collisions with the gas molecules to seriously affect the satisfactory operation of most magnetrons.

When a tube has been carefully exhausted and sealed off, it is necessary for the successful operation of this magnetron that a high vacuum, in the order of 5×10^{-7} Torr, be preserved within the envelope during the life of the tube. The envelope itself and the components for the X-band ICEM magnetron within the envelope will be made from materials which have a low vapor pressure, not only at the operating temperatures to which the tube is exposed on the exhaust pumps but also to temperatures occurring during unforeseen overloads in service. The materials chosen to join these components, such as brazing filler materials, will fulfill the same condition - they will not give off gases which would affect a vacuum of the order of 10^{-7} Torr.

In order to be able to take full advantage of the basically favorable vacuum characteristics of the chosen materials (Ref. 1), they must be in rigorously clean condition. Even during initial forming and machining operations, the end use in a vacuum must be kept in mind. Sulfur-free lubricants must be used for machining, drawing, stamping, etc. While surface films of oil are readily removed in the subsequent degreasing and cleaning operations, some microscopic pockets in the metal might be rolled over in machining, thus trapping oil or other contaminants which might not be released until much later when the part is in the tube. The presence of sulfur would then degrade the cathode, possibly to a point of complete poisoning and subsequent termination of oscillation.

In view of the extended life (10,000 hours minimum) for this magnetron, all internal tube components except the cathode components must be fired in hydrogen at approximately 1000°C to reduce remaining oxides and to outgas the bulk of the metal by replacing occluded gases with hydrogen which then easily escapes on the exhaust pumps.

All piece parts in the cathode structure will be fired in a vacuum furnace to accomplish pre-outgassing and to eliminate the possibility of oxygen release which has been observed to have harmful effects on impregnated cathodes at low pressures (less than 10^{-7} Torr).

This careful processing of the vacuum envelope components has been neglected for the most part since the average life of a conventional magnetron was not sufficiently long for the evolution of the entrapped gases to create a problem. However, as technology advances as in the case of the inverted coaxial magnetron and the average life of power tubes is extended to the thousands of hours plateau, more significance must be placed on materials and their relative cleanliness.

A significant portion of the work carried out on this contract, therefore, is taken up by mechanical design and materials processing to ensure that the end result will be a significant advance in long-life reliable performance.

1.2 The Inverted Coaxial Magnetron

The ICEM coaxial magnetron is a logical solution to cathode loading problem discussed above. Under another Air Force contract - AF 33(616)-7130 sponsored by the Electronic Technology Laboratory, Wright Air Development Division, Wright-Patterson Air Force Base - the ICEM magnetron was developed to produce a reliable high power oscillator at frequencies where conventional magnetron design was limited by size considerations.

The stabilizing cavity is in the structure center and is enclosed by the anode whose resonator vanes point radially outward instead of inward. The cathode surrounds the anode, which has an immediate advantage of increasing cathode area for a given number of resonators. A schematic of the mechanical layout is shown in Figure 1.

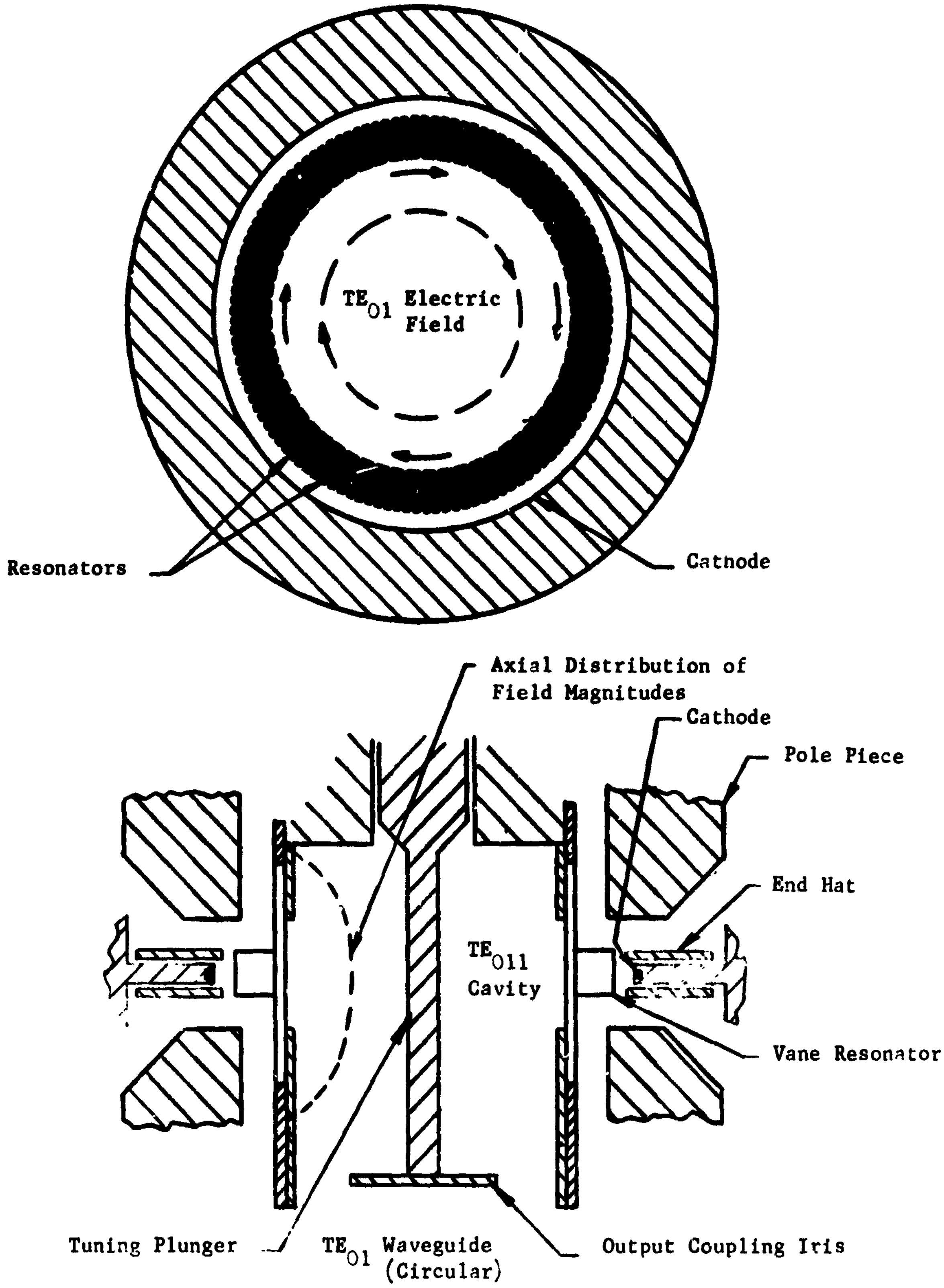


FIGURE 1 SCHEMATIC OF INVERTED COAXIAL MAGNETRON

Alternate resonators are slot coupled to the cavity as in the standard coaxial magnetron (Ref. 2). The operation and performance of the inverted coaxial magnetron are essentially the same with one exception, the method of output coupling. In the standard coaxial magnetron, power is coupled via a slot in the outer wall of the cavity and is fed through an appropriate impedance transformer to standard rectangular waveguide. Power is coupled out of the inverted magnetron through one of the cavity end walls and is fed axially into circular waveguide which, as an extension of the cavity, is driven in the TE_{01} transmission mode.

The large number of resonators possible with coaxial magnetrons has increased the anode and cathode areas so that higher power is possible without exceeding the specific anode dissipation and cathode emission current densities compatible with long life. The stabilizing effect of the cavity permits utilizing large numbers of resonators without the problem of mode separation encountered in conventional magnetrons.

1.3 The Engineering Specification

As a result of this program, an engineering specification for the SFD-328 has evolved. This document reflects the capability and limitations of the tube, as determined from data accumulated on the tubes built during the program. This specification is included in this report (Appendix I) with some changes required after evaluation of the most recent data, and also to clarify the description of some of the tests.

2.0 DESIGN REVIEW OF THE ORIGINAL SFD-328

Development of the SFD-328 was accomplished under Contract No. DA-36-039AMC-03304(E), sponsored by the U. S. Army Electronics Material Agency. This ICEM magnetron was a megawatt, tunable, pulsed, X-band circular waveguide output device, utilizing a solenoid for magnetic field supply. The tube is shown in Figure 2 with its required solenoid, which is shown in Figure 3. Since the above-mentioned contract was a feasibility study, no effort was made to incorporate features which would facilitate quantity construction.

The results of the second tube built on that program are summarized as follows:

Frequency	9.08 GHz
Pulse width	2.0 μsec
Duty factor	0.00004
Pulse voltage	36.5 kv
Peak power output	2.25 Mw
Average power output	90 watts
Anode current	150 amps peak

The tube had a narrow tuning range, and began to suffer the effects of heavy cathode current density after several hours of operation when a gradual degradation in cathode emission was observed.

2.1 Electrical Design Evaluation

2.1.1 Positive Pulse Input

Conventional magnetrons are constructed so as to require negative input pulses for operation. This is necessary since the anode, an integral part of the body, is difficult to insulate for the high voltage potentials required for magnetron operation. Grounded anode construction greatly facilitates the removal of heat generated on the anode structure due to anode power dissipation. Owing to the nature of the ICEM magnetron, it is possible to readily isolate the

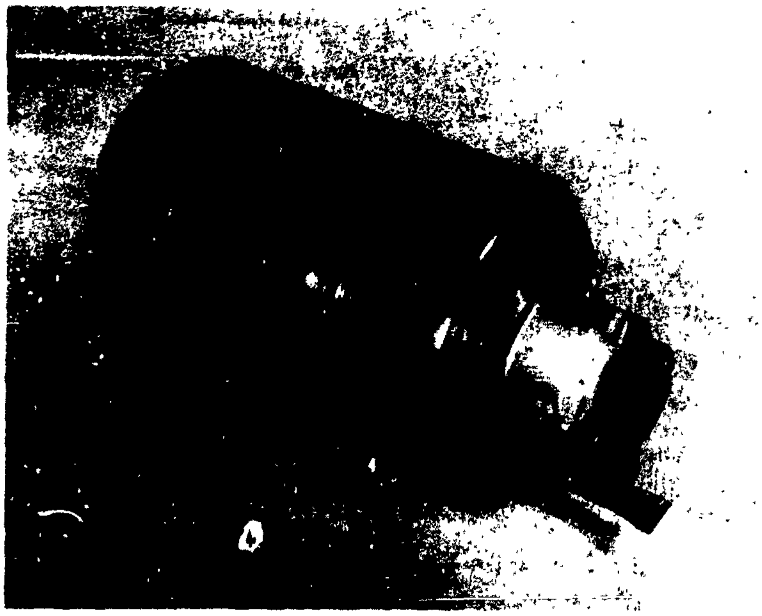


FIGURE 2 THE SFD-328 ICEM COAXIAL MAGNETRON, ORIGINAL DESIGN

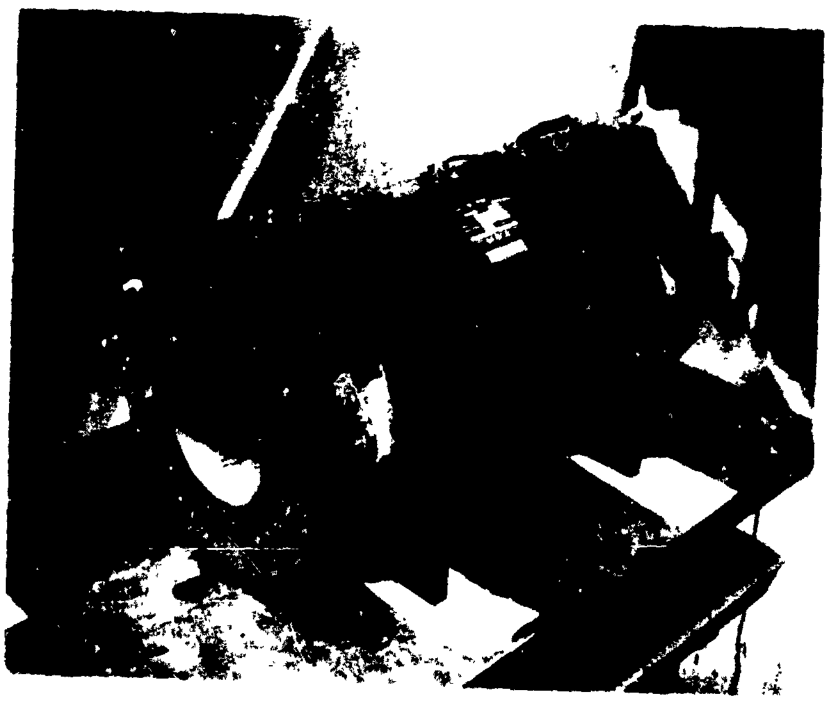


FIGURE 3 SOLENOID USED WITH ORIGINAL DESIGN SFD-328

anode electrically from the body of the tube and therefore pulse it positively. The SFD-328 was constructed in this manner. Benefits relating to voltage gradients, space charge focusing, and simplicity of cathode design could be realized using positive pulse type construction. However, the disadvantages also had to be enumerated in order to insure that the final approach employed in the redesign incorporated only those features consistent with the program objectives.

The objective of providing maximum utility in existing and in future systems was a key factor in determining which approach to employ. Positive input pulse requirements would certainly eliminate the general usefulness of this redesigned tube in existing systems which almost without exception provide negative polarity magnetron input pulses. Pulse transformers could be made to provide positive polarity; however, considerable effort would be required to adapt existing systems to this new polarity. Another factor which ruled out the positive pulse design was the difficulty of providing cooling in the high voltage region of the anode structure. Cooling the electrically insulated anode, of necessity would require the use of forced air. As a result, the operating anode temperatures for this insulated anode would be higher than is the case when the anode is connected directly to the grounded body of the tube. The reliability of this design would be lessened, since reliability always improves when critical component temperatures are held as low as is practical. Finally, the complexity of construction, particularly when tunability must be provided, was an additional disadvantage with the positive pulse design.

In view of these factors, the use of the positive pulse construction was ruled out in the redesign of the SFD-328. A negative pulse input was provided in the redesigned version of this tube.

2.1.2 Solenoid-supplied Magnetic Field

The SFD-328, as originally designed, obtained its magnetic field from a solenoid. This arrangement was employed to simplify the design of the tube so as to permit maximum effort toward the design of the cavity and interaction space geometry. As a result, the magnetic circuit design was incompatible with the requirements for permanent magnets in a fully packaged tube. Since no effort was made to minimize gap length and area, the magnetic circuit included in the SFD-328 required a prohibitive weight of magnetic material to provide operable magnetic field levels.

The redesign of the SFD-328, therefore, included a magnetic circuit design which complied with the requirement for minimum final tube weight.

2.1.3 Circular Waveguide Output

All the ICEM magnetrons developed by S-F-D laboratories had been constructed with circular electric mode output systems. This mode has very definite advantages in the millimeter region where its low relative transmission loss is valuable. At X-band in normal system use, this decrease in transmission loss is not significant.

Another distinct advantage gained when using the TE_{01} circular electric mode is in terms of peak power handling capabilities. At X-band, however, the rectangular waveguide system may be operated at peak power levels in excess of 1 Mw without undue problems in terms of high voltage breakdown.

Since the majority of systems in existence and those to be developed will require rectangular waveguide power, it would be necessary to provide a mode transition for use with a circular waveguide output version of the SFD-328. The development of such a mode transition to cover the expected 10% tuning range at the required 500 kw level would have required the expenditure of a major portion of the program effort.

The redesigned version of the SFD-328 provides direct rectangular waveguide output, precluding the need for a large and weighty mode transition.

2.1.4 Cavity-anode Considerations

The SFD-328 was designed and constructed to provide feasibility information and to verify scaling principles used to design tubes at different power levels and frequencies. Little emphasis was placed in this design on minimizing tube size or weight. The cavity and, therefore, the anode were designed according to the scaling principles only. As a result, the cavity diameter, if used in the redesigned version of the SFD-328, would have required a larger and heavier tube than program requirements dictated. By utilizing information gained through experience on prior ICEM development programs at Ka-band, it was possible to redesign the cavity to permit use of a smaller cavity diameter. A smaller cavity diameter resulted in a smaller diameter anode and cathode and, therefore, a smaller overall body, permitting a reduction in magnet weight. This enabled the redesigned SFD-328 to comply more closely with the program objective of minimum size and weight.

2.2 Mechanical Design Evaluation

2.2.1 Cathode Structure

The SFD-328 used a cold cathode made of beryllium copper, which has good secondary emission properties, and a button type coated emitter to supply the primary emission (see Figure 4). A structure such as this permitted the heater input power to be reduced substantially for a cathode of this size. However, owing to the complexity of such a structure, it was doubtful that the reliability and reproducibility requirements of this program could be satisfied.

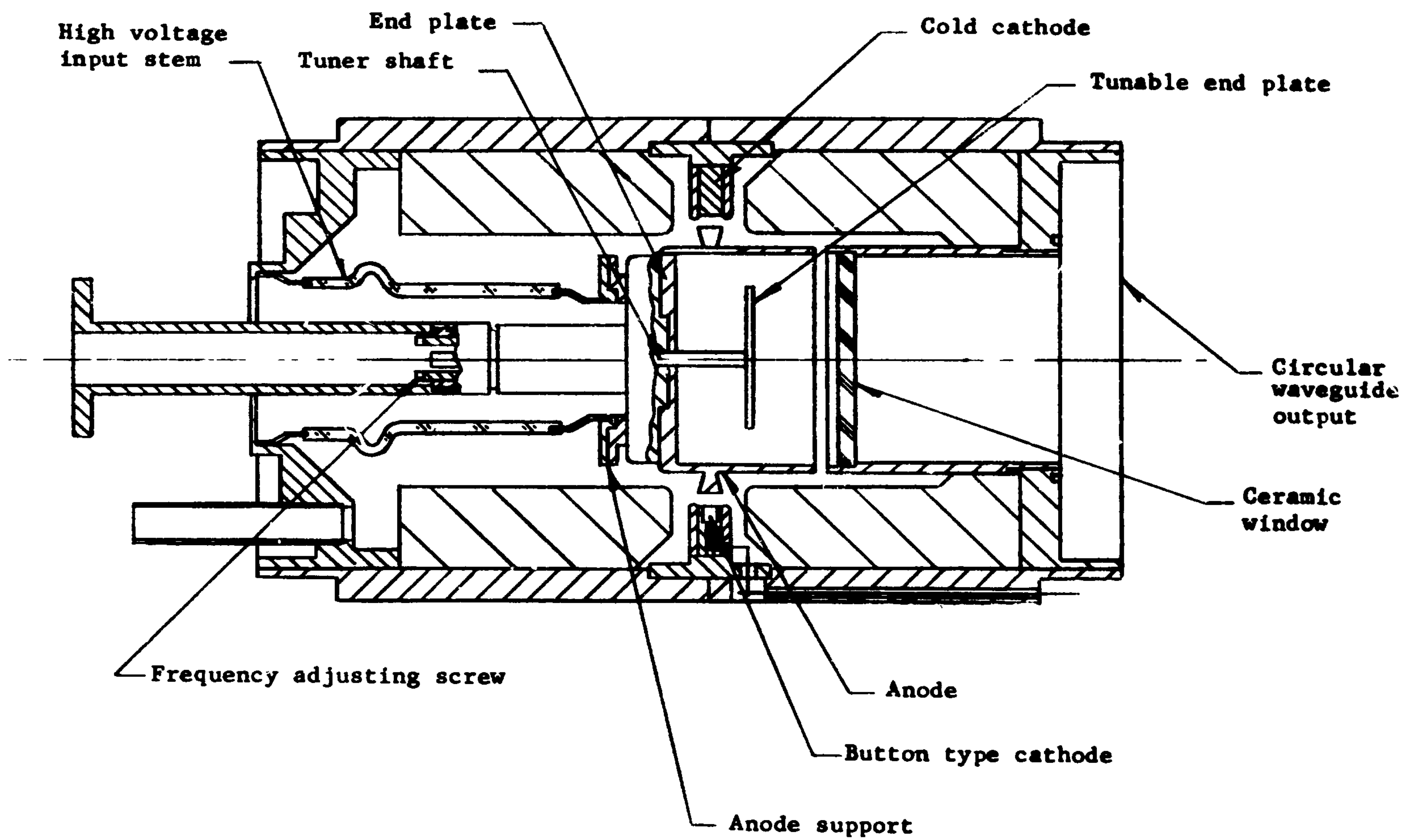


FIGURE 4 CROSS-SECTION OF THE SFD-328 ORIGINAL DESIGN

Currently, ICEM magnetrons manufactured at S-F-D laboratories employ dispenser type cathodes which have demonstrated the reliability and reproducibility capabilities necessary for this manufacturing methods program. Therefore, based on past performance, a dispenser type cathode was used in the SFD-328 redesign.

2.2.2 Cooling Provisions

The SFD-328 employed forced air cooling. The forced air was blown down the center of the solenoid which encapsulated the tube, producing an efficient means of cooling.

Liquid cooling is undesirable in a positively pulsed ICEM magnetron, since the anode is electrically and thermally insulated from the tube body. In order to cool the anode, the liquid coolant would have to flow in and around the high voltage stem to the base of the anode support. The size and weight of the tube would be increased if adequate plumbing were to be installed around the anode support.

Since the SFD-328 redesign is negatively pulsed, forced air or liquid cooling could be used without appreciably affecting the physical size and weight.

2.2.3 Package Design

The feasibility program conducted with the SFD-328 yielded a test vehicle which utilized a solenoid supplied magnetic field. Such a device was not consistent with the requirement for maximum utility in present and future systems. To be compatible with these requirements, the SFD-328 redesign incorporated permanent magnets with a tube mounting feature which is readily adjustable to existing equipment. Tunability was achieved through a conventional tuner mechanism which provides an economical and compatible design with existing systems.

3.0 INITIAL REDESIGN

In accordance with Exhibit "A", Phase I of this contract, the existing SFD-328 was evaluated in regard to its electrical and mechanical design characteristics. The following sections discuss the major considerations of this redesign.

3.1 Electrical Considerations

3.1.1 Cavity Design

The cavity design employed in an ICEM magnetron forms the basis for the complete tube design. Once the cavity dimensions are specified, all other tube parameters may then be specified. In addition to the normal cavity design requirements employed in coaxial tube design, the requirement of minimum size must be considered before the design may proceed.

3.1.1.1 Tuning Range

Minimum cavity diameter is normally determined by the tuning range desired and its proximity to the cut off frequency of the TE_{011} mode. Experience and practical tuning requirements, in terms of linearity and total tuner plunger traverse, determine the minimum practical diameter that may be employed. A cut-off frequency no greater than 75% of the lowest expected operating frequency must be employed to meet the practical tuning requirements. Using these criteria, the minimum cavity diameter can be calculated as follows.

$$D_m = \frac{c r_{\ell m}}{\pi f_m} \qquad (2)$$

where D_m = minimum diameter of cavity
$r_{\ell m}$ = mth zero of $J'_\ell(x)$, Ref. 3)
c = velocity of light
f_m = 75% of the lowest tuned frequency

In this application, the minimum tuned frequency is 8.6 GHz and, therefore, the maximum cut off frequency is (75% x 8.6 GHz)= 6.5 GHz. Using equation (2), the minimum diameter consistent with tuning requirements is 2.220".

A small diameter rod placed coaxially through the center of the right circular cylinder allows selective tuning of interfering modes. Modifications of the cavity diameter also allow selective tuning of interfering fixed-tuned TM modes which may produce power dips and mode contamination. Figure 5 shows the final theoretical mode chart obtained after incorporating some of the modifications mentioned above. The TE_{011} mode is capable of tuning the complete 8.6 GHz to 9.6 GHz range without crossing any interfering modes, when the cavity diameter is maintained within 0.080" of the practical lower limit.

3.1.1.2 Output Design

All ICEM coaxial magnetrons developed to date had employed a circular waveguide output coupling system. Figure 6 illustrates the type of coupling utilized in the SFD-328. The right circular cylinder was modified by a small diameter rod located coaxially. This rod supports a dual purpose cavity-terminating end plate and coupling disk. Because of its axial thinness, some of the TE_{011} mode energy couples past the disk through the output window to the load. By changing the diameter or the thickness of the disk, the coupling of the cavity to the load can be varied. Since the transmission characteristics of such a disk are a function of frequency, the coupling and therefore the output power differ markedly with frequency.

The redesigned SFD-328 had a rectangular waveguide output as illustrated in Figure 7. It can be seen that the end plate TE_{011} mode current stream lines intercept the radial coupling slot at right angles. Since the load can be represented as a resistance placed across this slot, the TE_{011} mode power is delivered to the load system. The

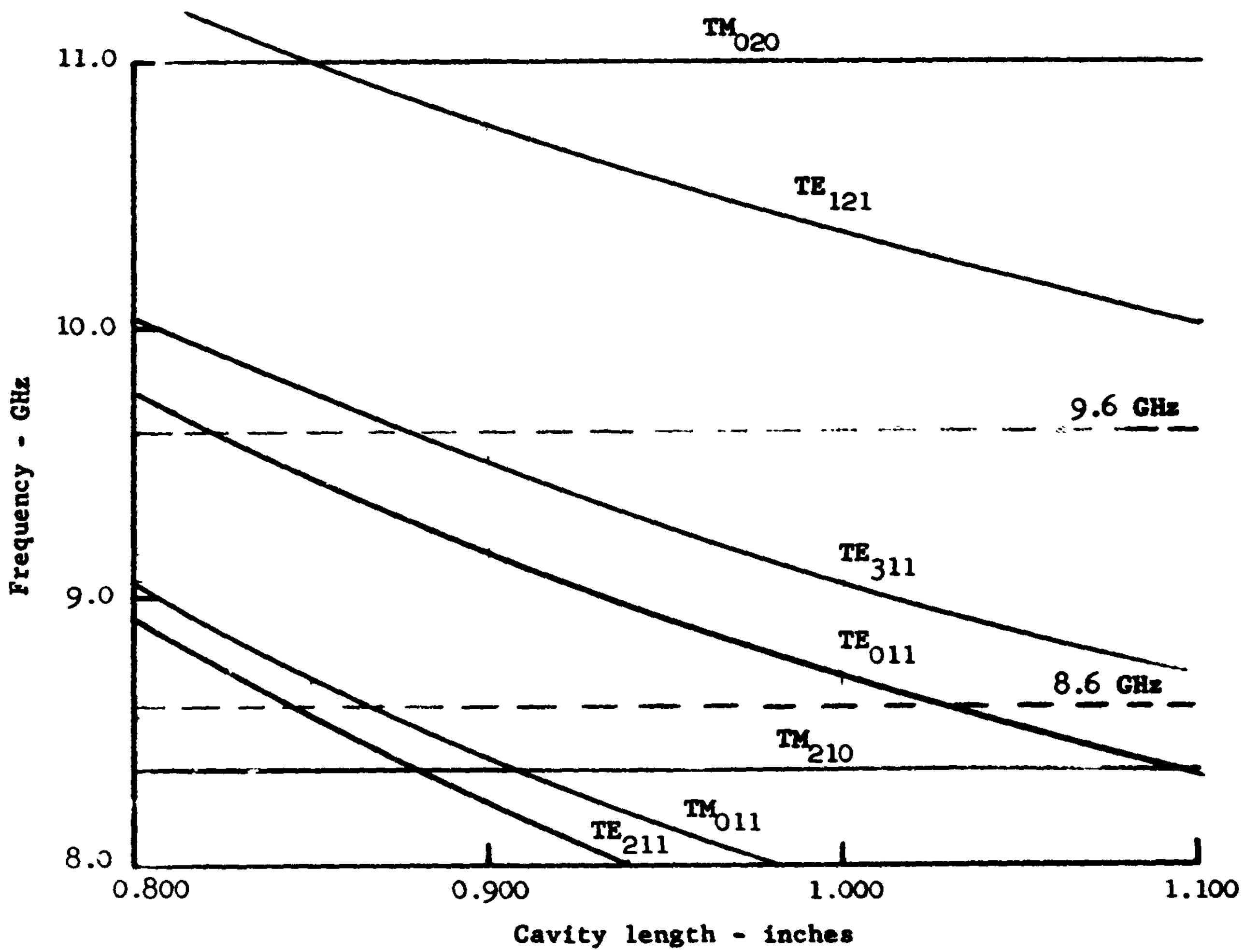


FIGURE 5 MODE CHART FOR 2.300 INCH COAXIAL CAVITY WITH 0.200 INCH DIAMETER CENTER ROD

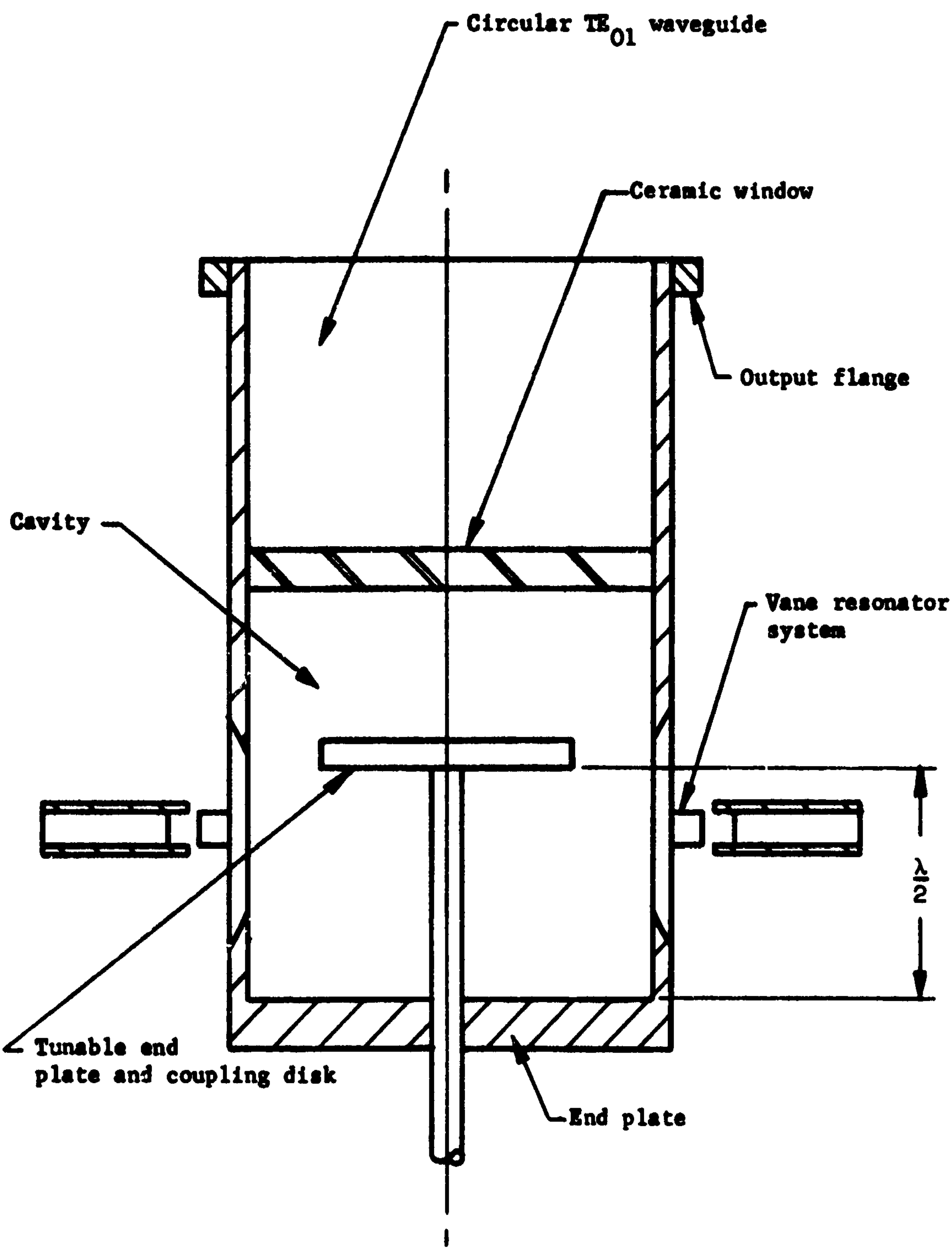
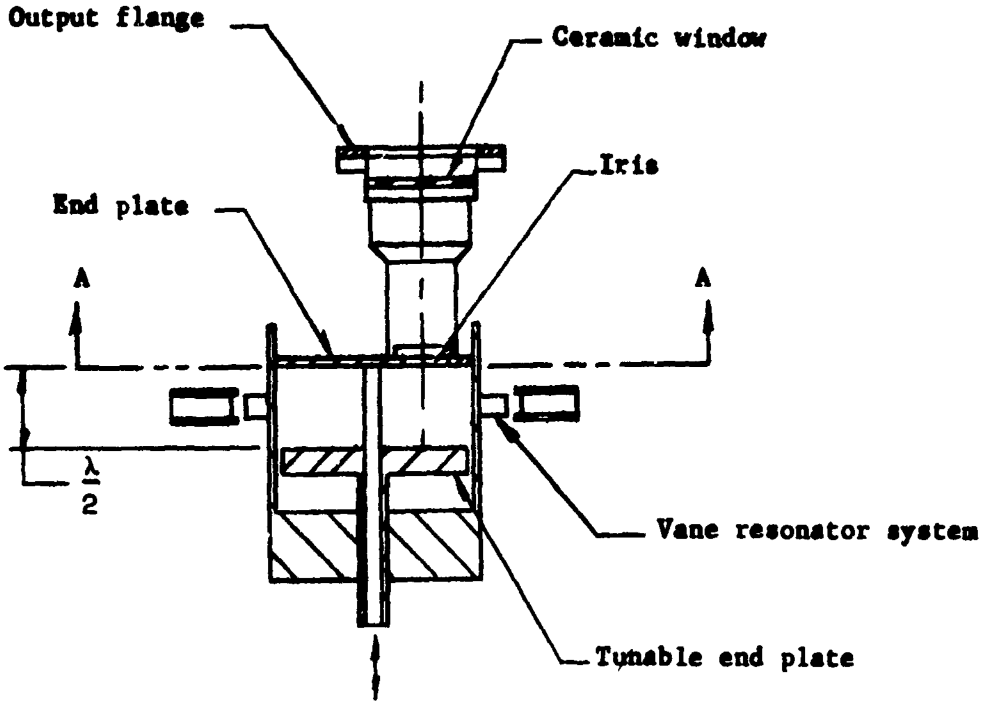
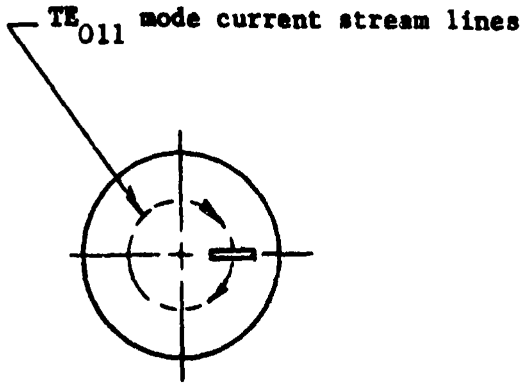


FIGURE 6 SCHEMATIC OF OUTPUT DESIGN FOR THE ORIGINAL SFD-328





End view of iris on end plate - View A - A

FIGURE 7 SCHEMATIC OF THE INITIAL REDESIGN OF OUTPUT SECTION nature of all other TE modes is to resist loading by changing rotational orientation so as to minimize coupling to the external system. Current stream lines associated with these modes line up to flow parallel to the radial slot and thereby provide no voltage across the slot which would represent external loading.

Figure 8 shows the method of mode suppression employed in the redesigned SFD-328. Since all TE modes except the TE_{011} mode present radial components of current flow across the cavity corner, a short section of coaxial waveguide is connected to the outer corner of the cavity floor. The undesired mode is coupled into this short transmission line which is terminated by an absorber. Since mode transformation can occur across the annular break in the cavity floor, all modes of interest may be propagated down this short section of waveguide, and thereby are loaded down.

The location of the radial output coupling slot and the competing TE mode absorber can be seen in the cross-section of the redesigned SFD-328, Figure 9. A double ridged waveguide transformer is used to match the coupling slot impedance to the higher impedance, connecting waveguide. The ceramic window used in this design has been proven in over the required frequency range at peak power levels of more than 1 Mw. The output connector is a modified UG-51/U cover flange.

3.1.1.3 Cold Test Verification of Cavity Design

It was necessary to construct a cold test model in order to evaluate the proposed design revisions. Figure 10 is a photograph of the cold test model. It was constructed in a manner which permitted evaluation of any configuration planned for inclusion in a hot tube. The parts are readily interchangeable, with provision for accurately measuring all critical dimensions.

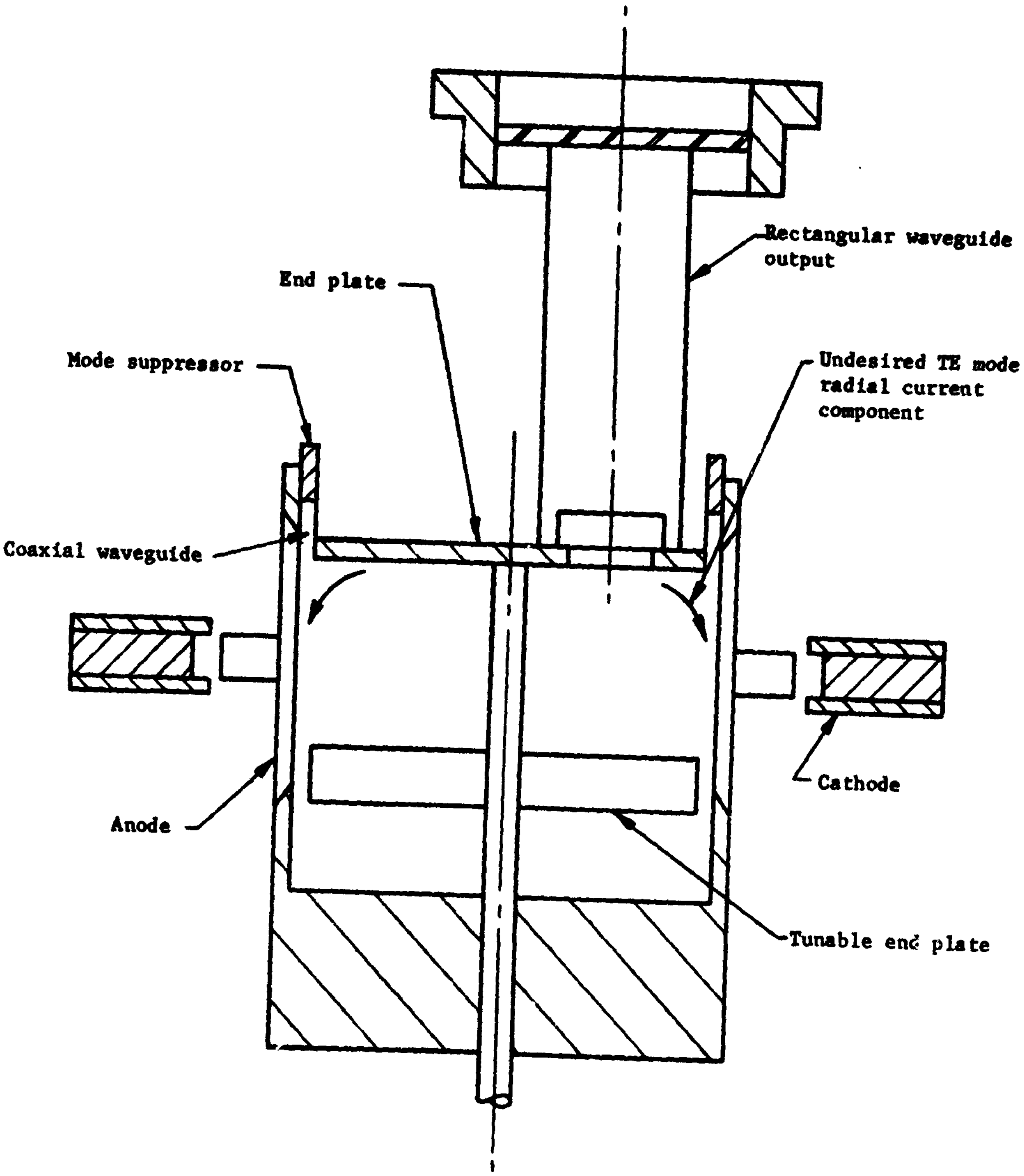


FIGURE 8 SCHEMATIC OF THE INITIAL REDESIGN SUPPRESSION TECHNIQUES

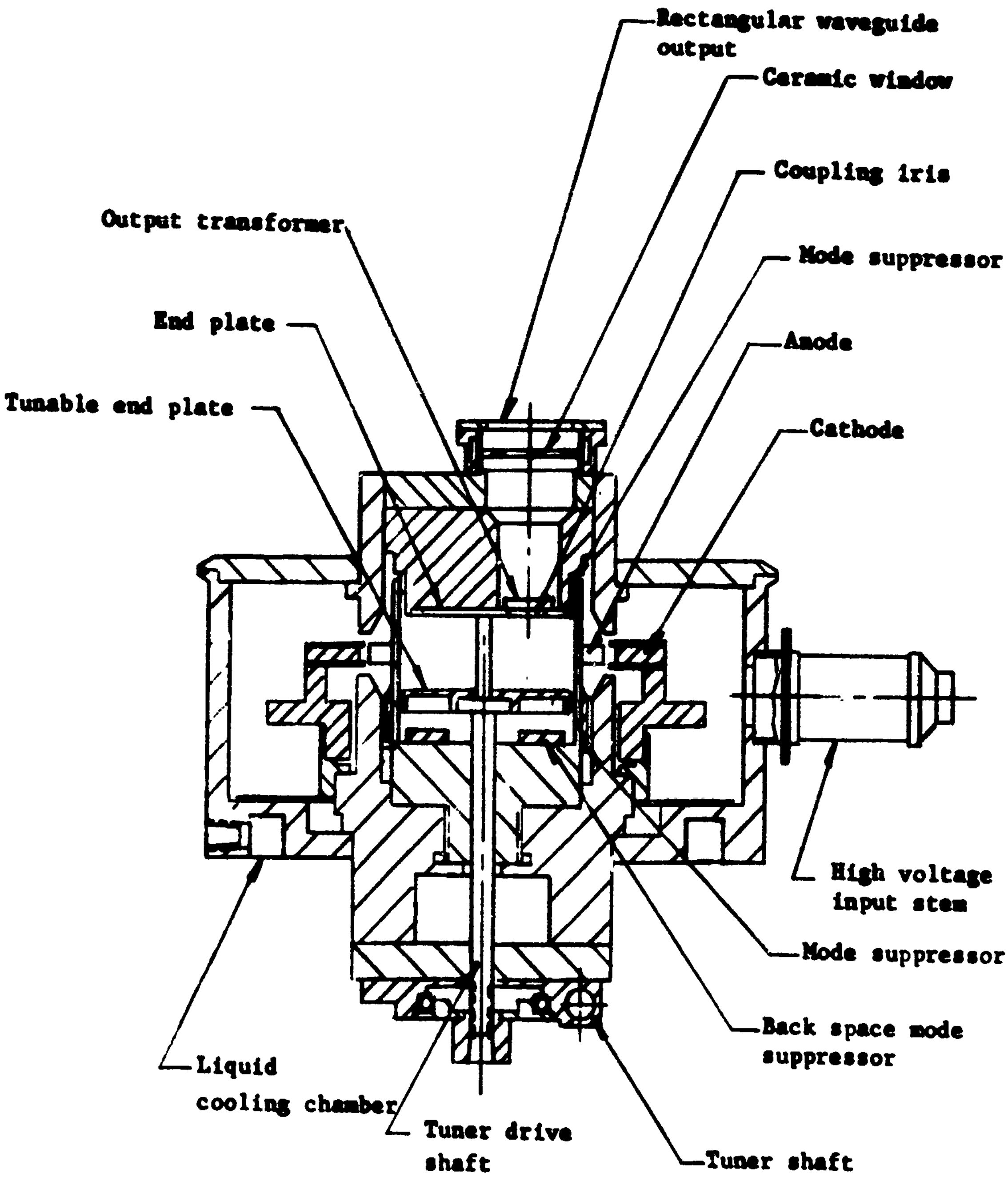


FIGURE 9 SCHEMATIC OF THE INITIAL REDESIGN SFD-328

FIGURE 10 COLD TEST MODEL CONSTRUCTED TO EVALUATE DESIGN REVISIONS

Initial measurements were made to verify the cavity design. An unslotted anode was used to remove the effects of the vane resonator and slot system from the cavity evaluation. As predicted from the mode chart constructed, no interfering modes were encountered as the desired TE_{011} mode was tuned across the required frequency band. Figure 11 illustrates the tuning curves of the actual cavity modes (dashed lines) in comparison to the predicted (solid line) cavity mode tuning curves.

Once the cavity design was verified, a series of cold tests were performed to insure the attainment of the required circuit efficiency across the 8.6 GHz to 9.6 GHz frequency band. The minimum value of circuit efficiency to be attained was 70%. Since the loaded Q of the tube must also be controlled, the minimum external Q can be given a lower limit. The following relation equates the parameters of interest.

$$Q_L = \eta_c Q_e \tag{3}$$

where Q_L = loaded Q

η_c = circuit efficiency

Q_e = external Q

Experience dictated that a loaded Q of 700 or greater was required. With this restriction together with the requirement of a 70% circuit efficiency, the minimum loaded Q was determined to be 1000.

A series of cold test experiments were performed to insure that these requirements were met while sufficient suppression of all undesired modes was also provided. It was possible to determine the degree of suppression of all possible competing cavity modes by direct Q measurement. All TE modes other than the TE_{011} mode are possible competing modes. The absorber, placed in the groove around the cavity outer diameter at the output end of the cavity, was very effective in

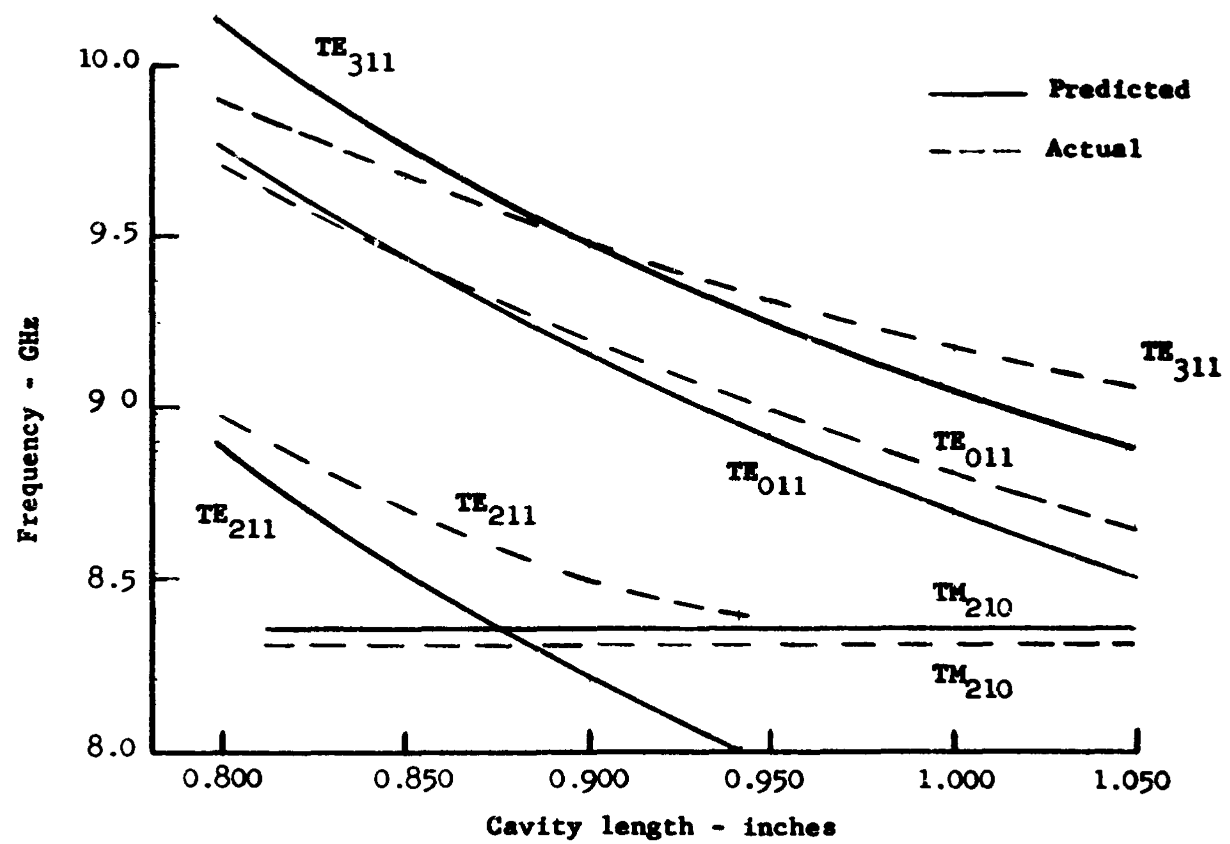
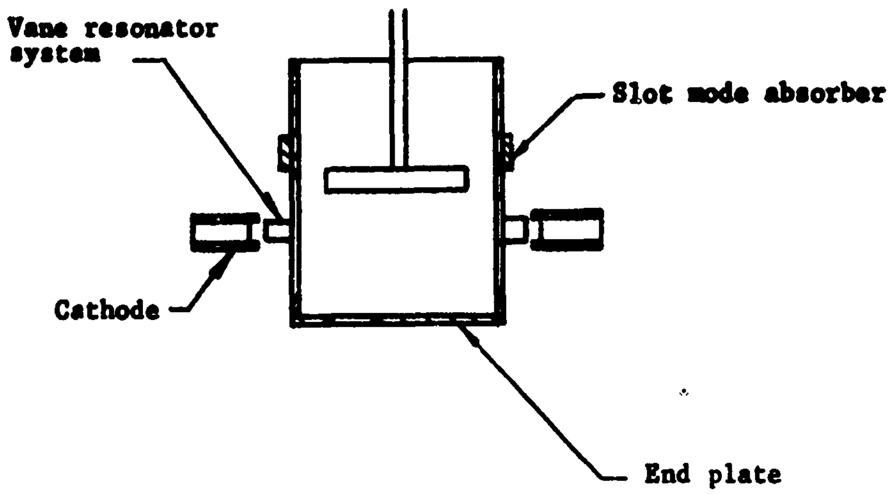


FIGURE 11 PREDICTED AND ACTUAL TUNING CURVES FOR X-BAND ICEM MAGNETRON

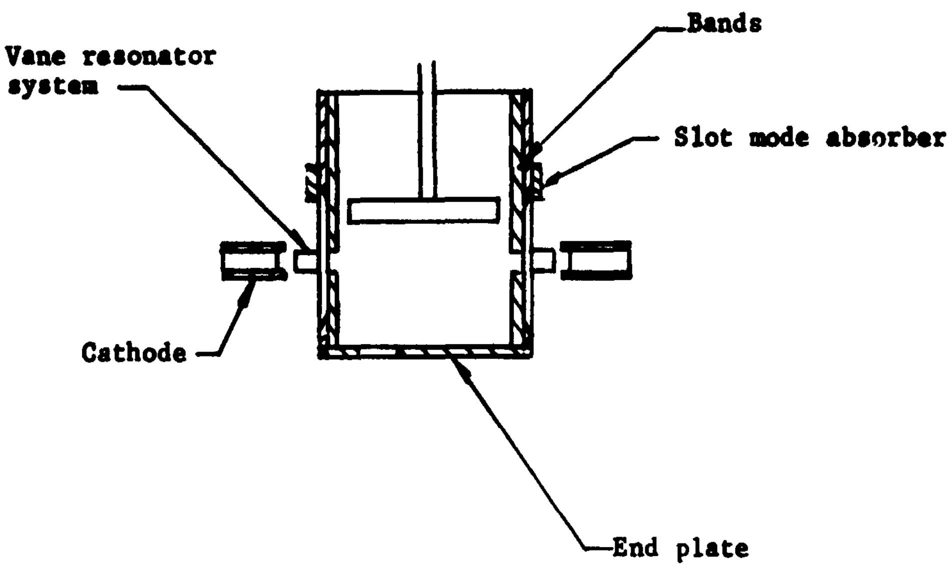
reducing the Q's of all undesired TE modes. This abosrber had no effect on the desired TE_{011} mode Q's. The presence of the slot mode absorber, however, is directly detectable in its effect on the desired TE_{011} mode Q's. It was necessary to provide, through cold test measurements, a level of slot mode suppression consistent with acceptable TE_{011} Q's in terms of the percentage of coverage of the anode slots. The level of suppression of the slot modes is not readily determined directly on cold test. Experience gained on other ICEM magnetrons indicates that minimum slot mode difficulties in tube operation will be attained if the maximum length of one end of the anode slot is covered by absorber material. All other dimensions of the standard carbon impregnated, porous aluminum oxide absorber are non-critical.

Cold test experiments were performed to optimize the unloaded Q of the TE_{011} mode over the required tuning range while permitting maximum slot mode absorber slot coverage.

As a result of these measurements two basic anode cavity configurations were found which satisfied the specified requirements. The first of these possible configurations is similar to the Ka-band ICEM design. In this design the vane resonator frequency is placed at the center of the tuning range. Vane resonator frequency is adjusted by modifying the length of the vanes in proportion to the change in resonant wavelength required. The vane resonator centerline is axially positioned at one-half the cavity height required to resonate the cavity at mid-band. A multiple segment, carbon impregnated band, which is placed around the anode outer diameter on the output end and covers a large fraction of the anode slots, suppresses the slot modes. A shield band is placed over the anode slots in the inner diameter of the anode to minimize the effect of this slot mode absorber on the TE_{011} mode unloaded Q. This configuration is shown in Figure 12b, with the resultant Q's shown in Figure 13. As can be seen in Figure 13, the coupling measured by the external Q is quite flat. The shape of this unloaded Q curve agrees with results obtained with Ka-band ICEM magnetrons.



a. Unbanded anode configuration



b. Banded anode configuration

FIGURE 12 COMPARISON OF BANDED AND UNBANDED ANODES

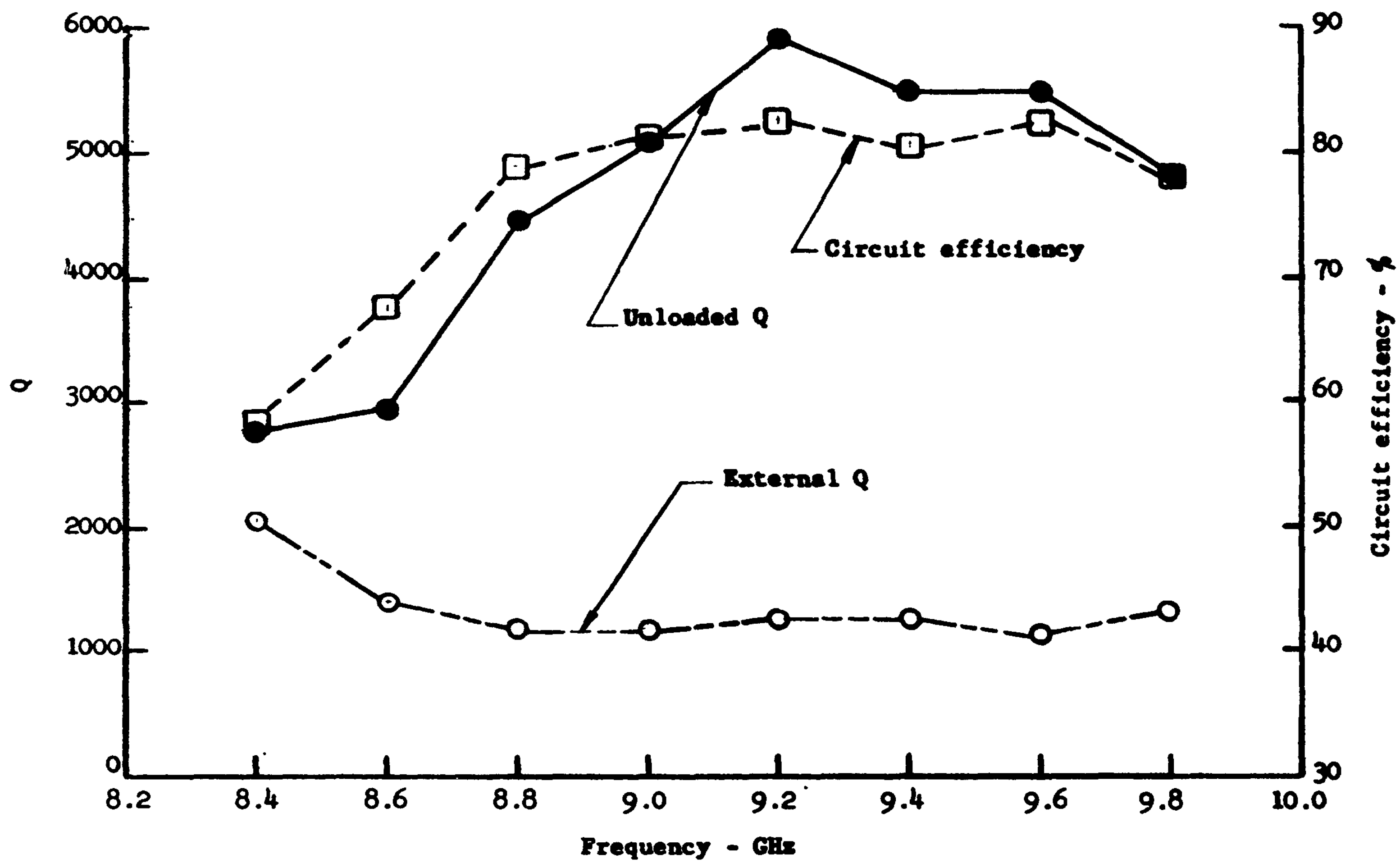


FIGURE 13 COLD TEST RESULTS OBTAINED WITH SHIELDED SLOT MODE ABSORBER CONFIGURATION

The second possible configuration, shown in Figure 12a, follows the design approach normally employed in the coaxial magnetron. The anode frequency is adjusted to the high end of the frequency range and the vane resonators are centered axially at the mid-band cavity height. The slot mode absorber is placed around the outer diameter of the anode on the end of the anode adjacent to the tuning plunger. Cold test results obtained with this configuration are shown in Figure 14. The circuit efficiency and unloaded Q are seen to be more nearly constant across the frequency band than with the first design described. A flat curve of circuit efficiency versus frequency is more desirable for inclusion in a hot tube. The output power, a direct function of circuit efficiency, will show less variation with frequency if the circuit efficiency is similarly held constant.

The output circuit design employed in both configurations is a design similar to that employed in the SFD-304 X-band CEM magnetron. Both the output transformer and the window are identical to those employed in the SFD-304 which operates over the same frequency band. Cold test measurements were made of the effect of output slot width changes on coupling level. As the output slot radial length is increased, the coupling increases uniformly across the tuning range. A width was determined which yielded the required external Q and then was specified for inclusion in the hot tubes.

3.1.2 Interaction Space Design

A tube which will develop 500 kw across the desired frequency range at the specified 1400 kw input power must have a minimum overall efficiency of 36%. A value of 40% was considered a safe minimum for use in the design of the interaction space. Since the overall efficiency is the product of the electronic and the circuit efficiencies, the minimum electronic efficiency could be determined once a minimum value of circuit efficiency was known. From the cold test results obtained, a minimum circuit efficiency of 70% could be safely specified. The

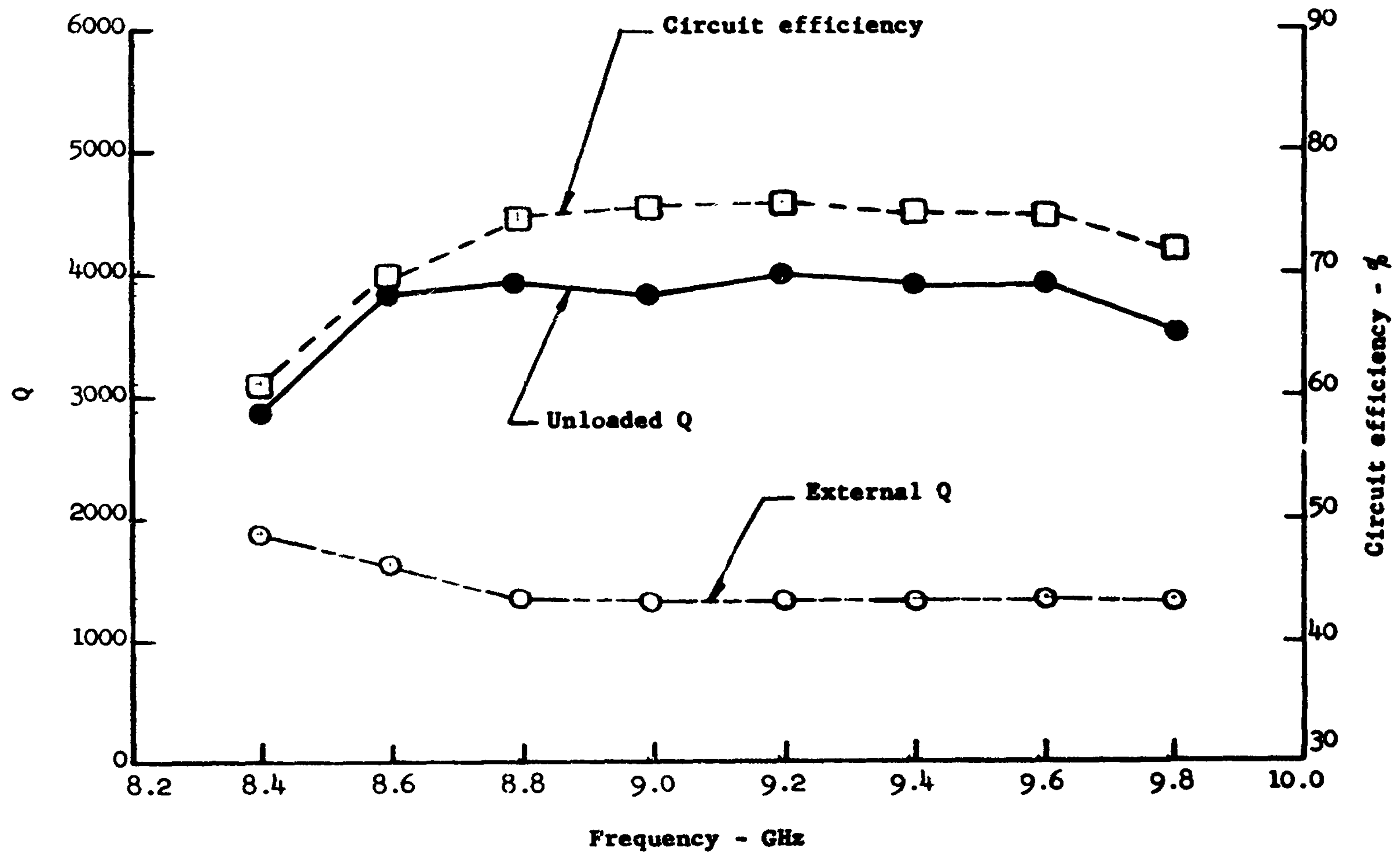


FIGURE 14 COLD TEST RESULTS OBTAINED WITH UNSHIELDED SLOT MODE ABSORBER CONFIGURATION

minimum electronic efficiency could now be calculated by

$$\eta_e = \frac{\eta_o}{\eta_c} \tag{4}$$

where η_e = electronic efficiency
η_o = overall efficiency
η_c = circuit efficiency

Thus, using equation (4) and the known values for minimum circuit efficiency and minimum overall efficiency, we determined the minimum electronic efficiency, η_e, required.

$$\eta_e = \frac{0.40}{0.70} \times 100 = 57.2\%$$

An anode vane circuit which satisfied this minimum electronic efficiency requirement had to have an operating voltage, V, to synchronous voltage, V_o, ratio of no less than 8. This ratio, together with the specified operating voltage, forms the basis for the anode design.

The synchronous voltage of the anode is determined by the following expression.

$$V_o = k\,\frac{(\pi D_a)^2}{n\lambda} \tag{5}$$

where D_a = anode diameter
n = N/2, where N is the number of resonators
k = a constant
λ = wavelength of the design frequency

With the anode diameter determined by the cavity diameter and the operating frequency, equation (5) was used to specify the number of resonators. Setting $V/V_o = 8$, the number of resonators required was 124.

Once the number of resonators was specified, the remaining interaction space parameters were readily scaled from existing ICEM magnetrons. The scaling laws thus determined the vane resonator height, cathode diameter, cathode emitter height, and end hat geometry. The Hartree equation was then used to indicate the magnetic field needed for operation at the required voltage level. In this design the magnetic field required in the interaction space was 4400 gauss.

3.2 Mechanical Considerations

3.2.1 Anode

The anode used in the SFD-328 is physically similar to but larger than a standard Ka-band anode, as can be seen in Figure 15. The techniques for producing both anodes are also similar.

3.2.2 Cathode Structure

The cathode structure of the inverted coaxial magnetron differs from conventional magnetrons in that it surrounds the anode structure. This increased emission surface area provides lower current density requirements. As a result, the magnetron has a longer electrical life.

Fabricating an inverted coaxial magnetron cathode at X-band is more difficult than at Ka-band or K-band because of the relative size. Figure 16 is a comparison of the X-band cathode and a Ka-band cathode. At higher tube frequencies, the tungsten matrix-molybdenum support combination used can be brazed without too much difficulty. The mechanical strength of the metals is sufficient to overcome the stresses which result from the difference in their thermal coefficients of expansion. At X-band, however, the tungsten matrix is too brittle to withstand such forces.

FIGURE 15 COMPARISON OF THE X-BAND ANODE (left) AND THE Ka-BAND ANODE (right)

FIGURE 16 COMPARISON OF THE X-BAND CATHODE (left) AND THE Ka-BAND CATHODE (right)

Several techniques were tried to pre-load the mating parts during the brazing operation but without success. To overcome the problem, the complete unit was constructed of porous tungsten, the matrix material. Tests were then made to evaluate the mechanical strength and vacuum capabilities of the structure. The structure proved to be satisfactory. The possibility of using a segmented matrix was discussed with the vendor, and it was mutually agreed that the best approach was to use the one-piece cathode.

The one-piece cathode also served to reduce the cost of fabrication by 36%. In this tube the cathode was mounted on an alumina ceramic support ring which also electrically insulated it from the tube body. However, to allow for the difference in thermal expansion between these two members, they were interconnected with several diaphram-type deflection straps. The deflection straps that connect the cathode to the ceramic support ring were fastened with the high temperature alloy machine screws. The use of screws permitted the cathode to be removed and replaced with relative ease, thereby permitting design changes to be made within the same tube body to reduce costs.

The deflection straps, which have a small cross-sectional area, were also used to impede the thermal flow from the cathode to the ceramic support ring. This impedance was necessary to achieve the heater-cathode warm-up time of five minutes.

To assemble the cathode concentric to the anode in the tube, a precision machined ring that mated with the outside diameter of the anode resonators was first placed around the anode. The cathode, which mated with the outer diameter of this precision ring, was then inserted over the precision ring. The deflection straps which were previously mounted on the cathode were then fastened to the ceramic support. After securing all screws, the ring was removed from the cathode and anode. A precision toolmaker's microscope was then used to measure the gap between the anode resonators and the cathode at six points which were approximately 60° apart. A total deviation between two opposite points could not exceed 0.0015". Generally, the concentricity was within this limit. If not, the fastening screws were loosened and the cathode was readjusted using the precision ring.

The end hats in a cathode assembly for the inverted coaxial magnetron also play an important role in tube life. The primary function of the end hat is to provide voltage gradients in the vicinity of the end of the interaction space. These voltage gradients form a focusing field. The focusing field shape can be maintained throughout tube life if dimensional stability is preserved.

End hats in an inverted coaxial magnetron necessarily have a large surface area. Cycling the cathode from room temperature to 900°C could easily induce buckling or warping in the end hats. To prevent this, the end hats are thermally isolated from the cathode, thus limiting the temperature variation of the end hats during thermal cycling.

Figure 17 is a physical size comparison of the end hats used in this X-band magnetron and a Ka-band magnetron.

The cathode assembly constructed was designed to allow numerous changes. Parts which were not permanently fixed could easily be removed or added, thus permitting rapid and economical evaulation of design changes.

3.2.3 Heater Design

In a long life magnetron, new areas of concern appear in that all components of the tube must be capable of appreciably longer life. Of particular concern in this area is the heater.

The heater in an ICEM coaxial magnetron requires scrutiny for two reasons - the first is the nature of the design which employs a long, small diameter wire; the second is the large surge currents which occur during heater input power snap-on.

The SFD-328 redesign required a heater capable of no less than 1000 on-off cycles and 10,000 hours minimum life. The design

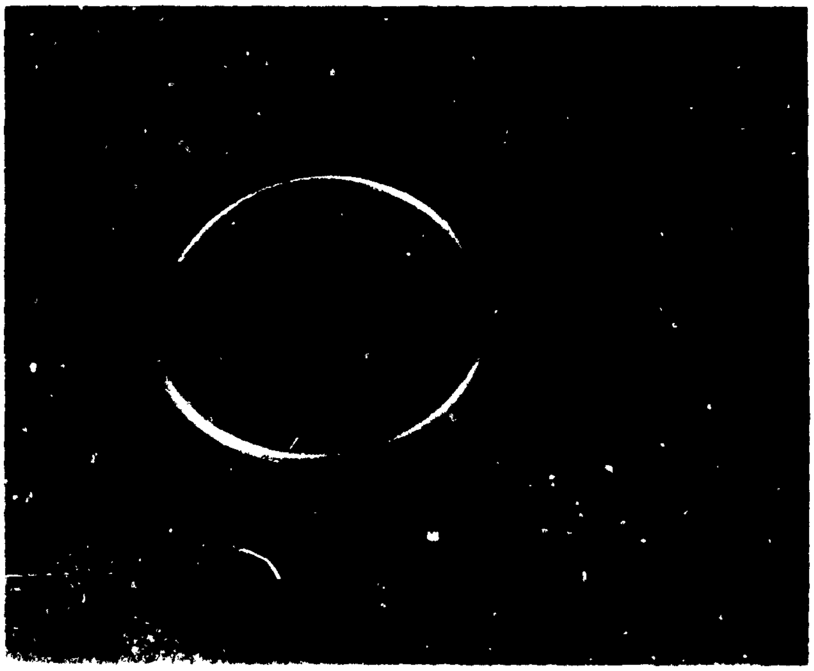


FIGURE 17 COMPARISON OF THE X-BAND END HAT (left) AND THE Ka-BAND END HAT (right)

selected for the SFD-328 was based on previous experience with the reliability and life performance of the heater design in the SFD-315 and the SFD-319 ICEM coaxial magnetrons.

3.2.4 Tuner Design

The SFD-328 tuner design in Figure 9 is similar to that used on a cavity wavemeter. Tuners of similar design had previously been used in other inverted coaxial magnetrons and had been tested to 300,000 cycles without failure. The external tuner drive consisted of a conventional drive mechanism for maximum system utility.

3.2.5 Magnets

The redesign of the SFD-328 required that size and weight be minimized. Further consideration thus had to be given to the magnetic circuit necessary to provide the magnetic field. No effort was made to restrict the size of the original SFD-328; hence using pole pieces of similar design was not practical. In addition, existing Ka-band ICEM magnetrons were of little value in solving this problem. The very high value of interaction space magnetic field used at Ka-band required relatively large pole pieces to minimize saturation effects. Pole pieces scaled from Ka-band to X-band were too large to be of value. To accomplish this size reduction, electrolytic tank plots were made with the goal of obtaining a field shape similar to that employed in the Ka-band ICEM magnetron with minimum gap length and pole piece area as the requirements. The field shape required was linear in that no variation in the axial field was desired over the interaction region. The pole piece dimensions determined in this manner were included in the initial hot tube models.

3.2.6 Cooling Provisions

The tubes constructed in this program were liquid cooled since no additional hardware was required, with the exception of liquid pressure fittings. In addition, design of the permanent magnets was simplified by the omission of air cooling ducts.

3.3 Evaluation of Hot Tube

The first hot tube model was constructed in late December 1965 and reached test during the first week in January 1966. This tube, A9H, is shown in Figure 18 with the vacuum appendage pump attached. An electromagnet was used on these early tubes to supply the magnetic field. This procedure was followed until the magnetic circuit was thoroughly proven. Once the pole piece design was frozen, sufficient information was available to arrive at design parameters. Permanent magnets were then used.

Desired mode operation was attained across the complete tuning range when the tube was placed on hot test. Operation at magnetic field levels approaching the design level was not possible, however. Rapid increase in gas pressure within the tube and heavy arcing precluded operation at input voltages above 25 kv. Figure 19 shows output power versus frequency for this tube.

The data shown in Figure 19 were accumulated at input conditions well below the specification requirements. Such data, however, helped to determine the effectiveness of the output coupling system and were of value. Power output across the required tuning range did not vary significantly, demonstrating the usefulness of the output system design.

Measurements demonstrated that a five-minute cathode warm up time was feasible. Usable cathode temperature was attained in approximately six minutes with a heater input power of 200 watts. In actual system operation, a filament transformer with normal regulation will deliver more than 200 watts initially. This input power then stabilizes at 200 watts when the cathode reaches equilibrium temperature. The cathode temperature therefore was adequate for operation within the required five minutes.

No evidence of operation in any of the competing TE cavity modes was detected up to the 25 kv input voltage level. Operation

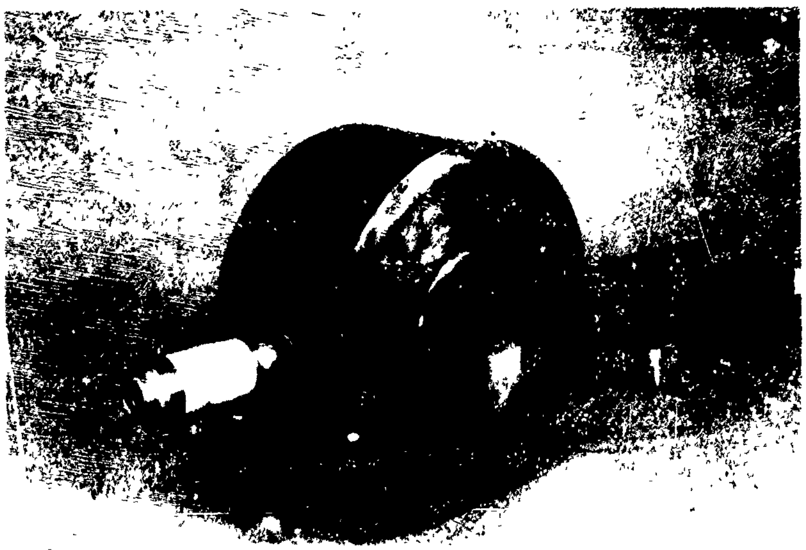


FIGURE 18 FIRST HOT TUBE MODEL, A9H

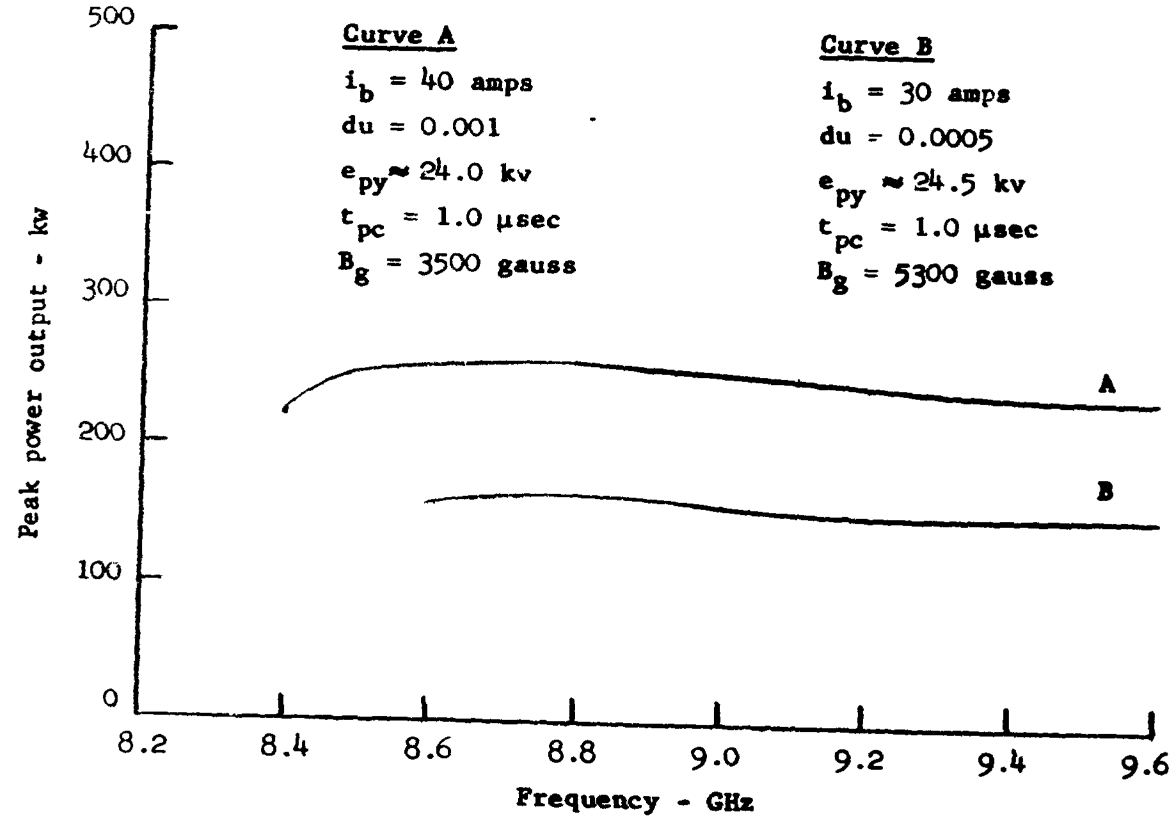


FIGURE 19 PEAK POWER OUTPUT VERSUS FREQUENCY FOR FIRST HOT TUBE, SERIAL No. A9H

at the higher voltage levels was not possible. Therefore, evaluation of future tubes was necessary to insure that the method of suppressing competing TE cavity modes was adequate.

The tube was opened after operation to determine the cause of the arcing which occurred as normal operating voltage levels were approached. Considerable evidence of arcing was noted on the inside surface of the end hats opposite the vane resonators. The voltage gradients in this region are the highest encountered in the tube, approaching 1000 volts per mil. This gradient value has been exceeded in Ka-band ICEM designs, but with crossed magnetic fields of over 10,000 gauss. At lower levels of magnetic field, the maximum allowable gradient must be reduced. Tube A9H was then rebuilt with increased end hat spacing to reduce the voltage gradient to a safer 600 volts per mil level.

A total of three more test vehicles were constructed using the original mechanical configuration. These tubes and their rebuilds showed problem areas and allowed for changes which resulted in solutions. Design modifications had to be made to correct for instability at high magnetic field values and low overall efficiency. The major change was a reduction in the number of resonators from 124 to 108.

Figure 20 shows the performance characteristics of tube D42H, and is representative of the results of the initial redesign phase of the program.

In summary, the results of the initial redesign did not meet full expectations. The overall efficiency associated with good RF stability was low. Mechanical problems existed in the cathode support structure and were still not entirely solved at the completion of this phase. Prolonged delays in delivery of support ceramics led to construction delays, and it was decided to begin construction of the final design tubes with an intermediate design of the cathode support ceramic.

	Curve A	Curve B	
i_b	70	60	amps
du	0.0005	0.0005	
e_{py}	≈27	≈27	kv
t_{pc}	1.0	1.0	μsec
B_g	4100	4100	gauss

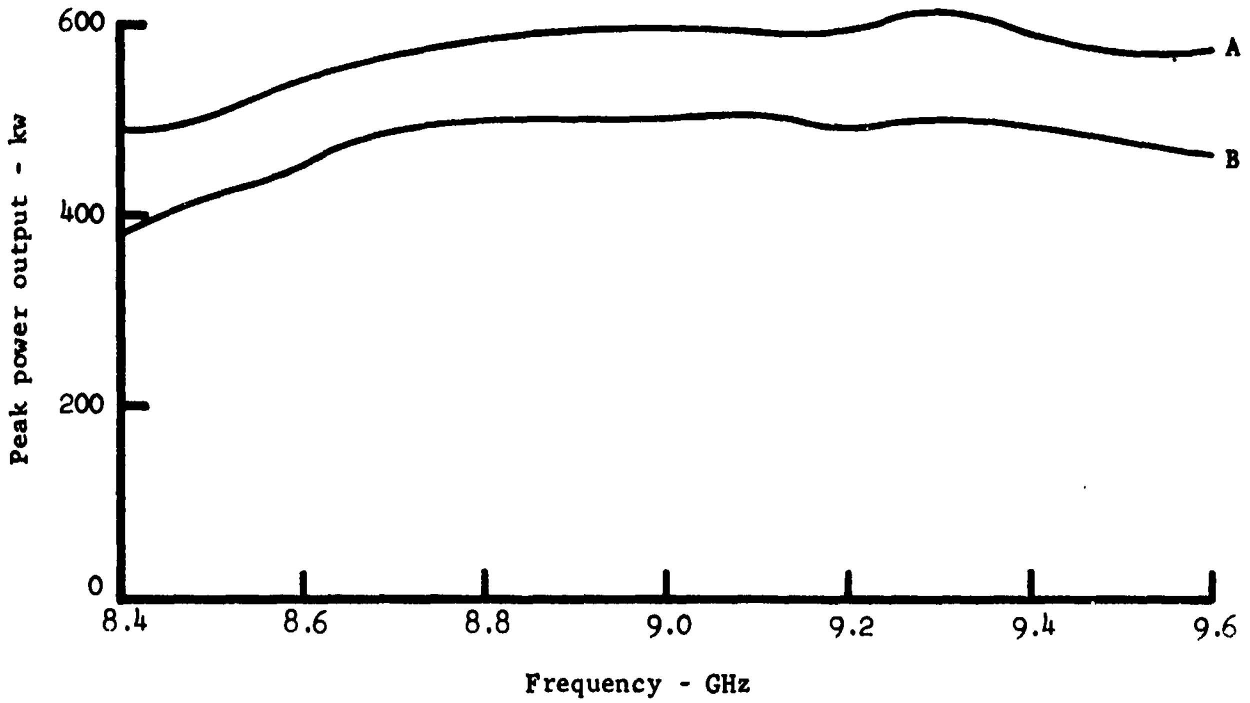


FIGURE 20 POWER CHARACTERISTICS OF TUBE D42H

4.0 FINAL DESIGN

4.1 Electrical Considerations

The final design tubes, with the exception of one, were built with 108 resonator anodes. As indicated in the preceding section, this design was the most reliable of all that were built. The major problem area of the tube was still the cathode support structure, which allowed the cathode to move off center due to thermal cycling. This eccentricity caused a gradual decrease in tube operating voltage and lower efficiency. Thus, the greatest effort during the final design phase was placed on improving the mechanical characteristics of the tube.

4.2 Mechanical Considerations

4.2.1 Anode

The anodes that were made in the initial phase of the contract were fabricated by precision adaptation of conventional methods; that is, by turning and slotting. These methods have proven themselves reliable and economical over other methods such as hobbing and electrical discharge (spark erosion) machining. These techniques were evaluated on a previous contract, AF 33(657)-9970.

The anode design used during the initial phase of the contract contained a threaded shank which permitted easy installation and removal. Several anodes with different geometries were thus evaluated in the basic body structure. The thread locked the anode in the tube body sufficiently without brazing. Figure 21 shows the anode with the threaded shank as compared to the final configuration brazed-in anode.

The final anode design shown in Figure 21 also had a small thread on its shank as a means of supporting the anode during the brazing operation. The remaining portion of the shank was extended to facilitate external liquid cooling and to provide tuner shaft bearing support.

FIGURE 21 INITIAL ANODE DESIGN AND FINAL ANODE DESIGN

4.2.2 Cathode Structure

The cathode assembly which consists cf the cathode emitting surface, end hats, heater, supports, and heat shields is one of the high value items in any magnetron. The cathode structure of the inverted coaxial magnetron differs from conventional magnetrons in that it surrounds the anode structure. Since the physical size of the inverted cathode is much greater than the conventional cathode, the surface area of the emitter is also much greater which decreases the current density requirements. As a result, the inverted coaxial magnetron has a longer electrical life, provided no compromises are made in the quality of the cathode.

The cathode support design in the inverted coaxial magnetron is more complex than the cantilever support used in the conventional magnetron. More hardware is necessary to properly support and electrically insulate the larger cathode ring during all phases of processing and thermal cycling. The structure must be capable of withstanding environmental conditions of vibration and shock, and still maintain a cathode-anode concentricity of 0.002" TIR.

Another relatively important consideration is that the heating element must be capable of heating the cathode to the operating temperature (850° to 875°C) with a reasonably low value of heater input power. Heater dissipation through conduction and radiation throughout the cathode support assembly must be minimized to achieve low heater input power. The cathode shown in Figure 22 was mounted on six deflection straps which were used to impede the thermal flow from the cathode to its supporting member, thereby reducing the heater-cathode warm-up time and heater input power. The straps also provided a mechanical means to overcome the thermal expansion differences between the cathode and its supporting members during all phases of processing. A more rigid design without deflection straps would cause the thin-walled cathode member to become distorted during processing.

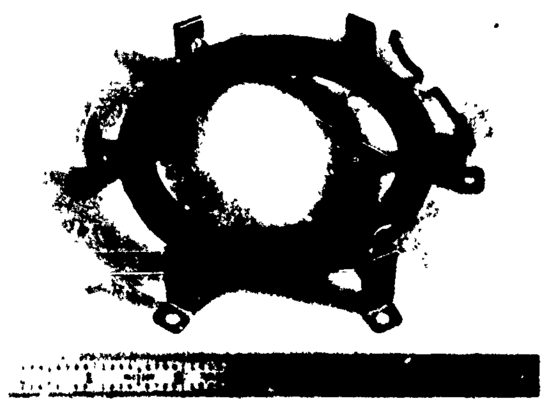


FIGURE 22 CATHODE WITH DEFLECTION STRAPS

The cathode was designed with a small cross section and minimum mass to permit the cathode to warm up within 300 seconds. In addition, the cathode was mechanically isolated from the end hats which also function as heat shields to reduce the heat radiation from the cathode body. Figure 23 shows the cathode assembly mounted on the ceramic support ring in a vacuum bell jar. The cathode was completely surrounded by the end hats and ceramic segments except for the cut-out section required for the deflection straps and the emitting surface of the cathode which faced the anode. Figure 24 shows the cathode glowing in the bell jar when the heater power was applied. Note the relatively low temperature of the components surrounding the cathode when the cathode temperature was 1000°C. No temperature color change was noticeable on the upper end hat nor on the outer portions of the deflection straps.

During the early phases of the program, the cathode was held in place temporarily by high temperature alloy screws which permitted design changes in less time and at minimum cost. When the electrical design was finalized, these screws were brazed to the cathode body and the deflection straps, as shown in Figure 22, to provide a permanent means of fastening. Since the cathode now was more rigid, a problem was encountered with the brittle, porous tungsten from which it was fabricated. The cathode had six mounting projections which extended from its outer diameter and formed an integral part of the wall. However, this circular portion of the wall did not have the strength to withstand some of the forces which were applied when the cathode was fastened to the body assembly. Unless extreme care was taken during the assembly of the cathode, the outer wall of the cathode body would fracture. Since all of these parts had been received when the final build schedule began, no corrective action with regard to the wall thickness of the cathode could be implemented because of long lead times. The corrective action necessary was to increase the wall

FIGURE 23 CATHODE ASSEMBLY MOUNTED ON A CERAMIC SUPPORT RING IN A VACUUM BELL JAR

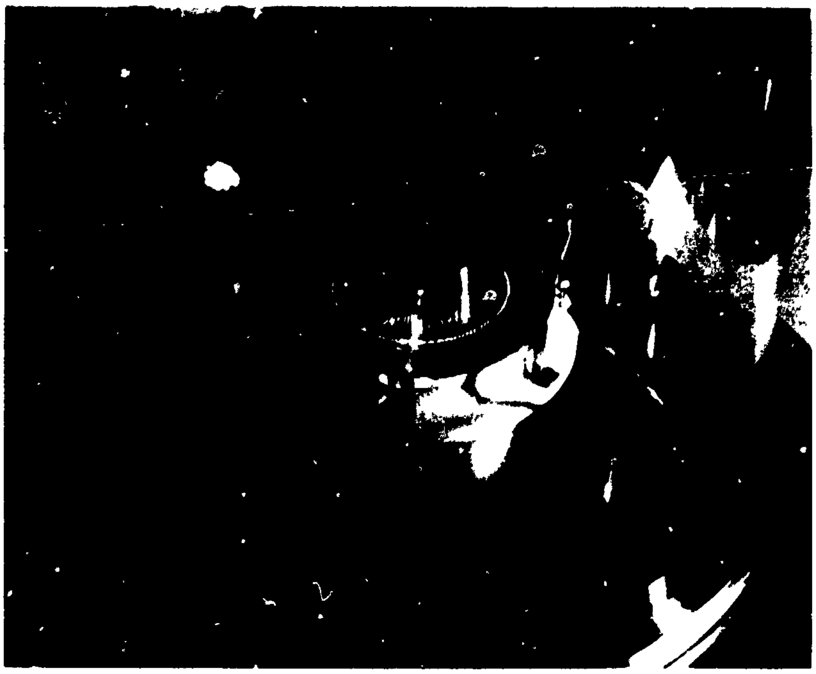


FIGURE 24 CATHODE ASSEMBLY IN VACUUM BELL JAR WITH HEATER POWER APPLIED

thickness of the cathode body by increasing the outer diameter of the cathode by 1.5%. This would increase the strength factor of the wall thickness by 1.9, thereby eliminating the critical nature of handling the cathode while it was assembled to the body.

As discussed earlier in this section, the original cross-sectional design of the cathode considered minimum mass as a prerequisite to achieving cathode warm up within 300 seconds. With the increase in cathode diameter as anticipated above, the overall mass of the cathode assembly would be increased by 8.5%. The cathode warm-up time might still be achieved within the present specification by using the upper limits of the input power. The heater filament is rated at 1.5 times its present capabilities so that any additional input levels required are well within the realm of the heater design.

The operating temperature of the end hats in an inverted coaxial magnetron also plays an important role in tube life. The primary function of the end hat is to provide voltage gradients in the vicinity of the interaction space. These voltage gradients form a focusing field whose shape can be maintained throughout tube life if dimensional stability is preserved. To accomplish this dimensional stability, the end hats are thermally isolated from the cathode to eliminate buckling or warping in the end hats which may be induced by temperature differences during thermal cycling. The operating temperature of the end hats was reduced by 350°C with the end hats mechanically and thermally isolated from the cathode. Figure 25 shows the end hat used in the SFD-328. The formed ridge on the surface of the thin member increased its strength and maintained flatness.

The cathode assembly and end hats were mounted on a high alumina ceramic support ring shown in Figure 26. The ceramic material was used to electrically insulate the cathode structure from the tube body and to impede the thermal flow from the cathode structure to the tube body. In addition to these two factors, the ceramic support

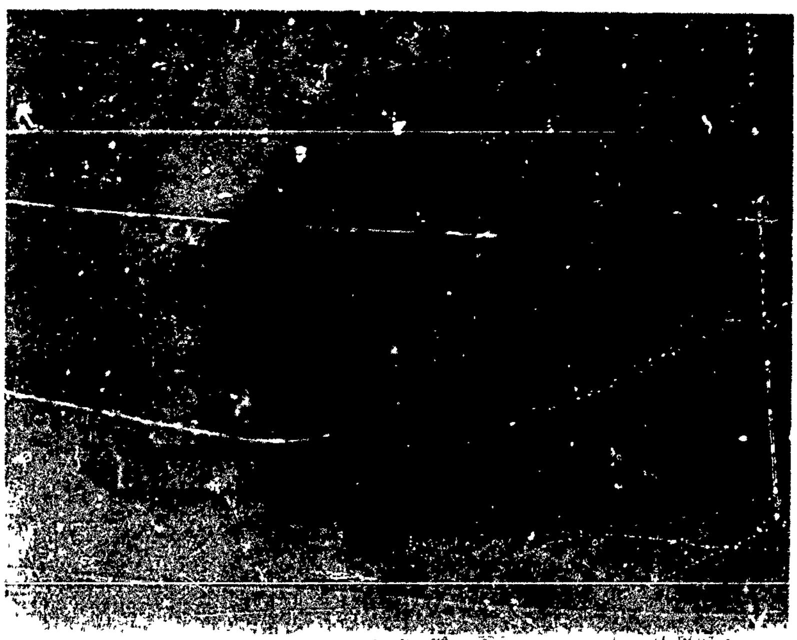


FIGURE 25 SFD-328 END HAT

FIGURE 26 CERAMIC SUPPORT RING

provided a very rigid, one-piece mounting base for the critical interaction spacings which had to be maintained for electrical stability. To provide additional assurance that the interaction spacings were maintained, the anode and the ceramic support ring were mounted and brazed to the same component in the tube body; that is, to the anode pole piece. Figure 27 shows these units assembled in the tube body. To produce a mechanical bond between the ceramic support and the iron pole piece, the inner surface of the ceramic was metalized as shown in Figure 28. A ductile member, such as the arrestor shown in Figure 29, was inserted between the iron pole piece and the ceramic support in order to form the braze. The arrestor was required in this assembly since the thermal coefficients of expansion between the iron and the alumina ceramic were such that the ceramic would crack under tension during the high temperature braze or during bake out at tube evacuation. Figure 30 shows the completed cathode assembly and the anode assembly prior to final seal in.

Many problems were encountered in the manufacture of the ceramic support because of its physical size, shape, and tapped holes. The initial design of the ceramic support consisted of a similar shape. However, the tapped holes in the inner bolt circuit were not through holes. As a result, the bottom portion of the hole was highly stressed when tapped in the semihard ceramic. Upon subsequent heat treating, the ceramic cracked through the tapped holes.

After consultation with the vendors, a redesign was made which consisted of two pieces, an upper and a lower ring. The upper ring, Figure 31, consisted of clearance holes for the mounting screws and the lower ring, Figure 32, consisted of tapped holes through the cross section to eliminate the highly stressed regions. The lower ring was then capable of withstanding the subsequent heat treating. After evaluating this design in a tube, it was found that electrical breakdown occurred at 21 kv through the upper and lower sections of ceramic

FIGURE 27 ANODE AND CERAMIC SUPPORT RING BRAZED IN TUBE BODY

FIGURE 28 METALIZED CERAMIC SUPPORT RING

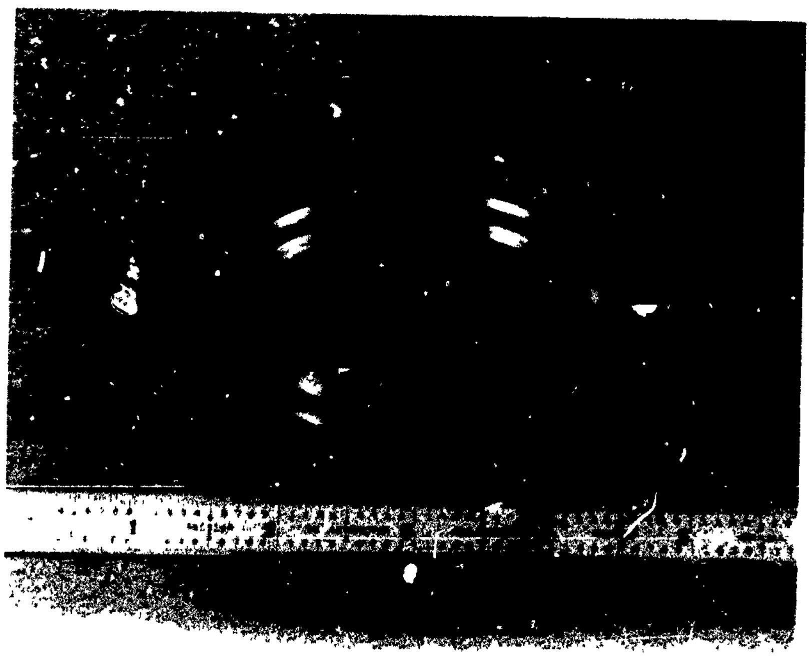


FIGURE 29 ARRESTOR

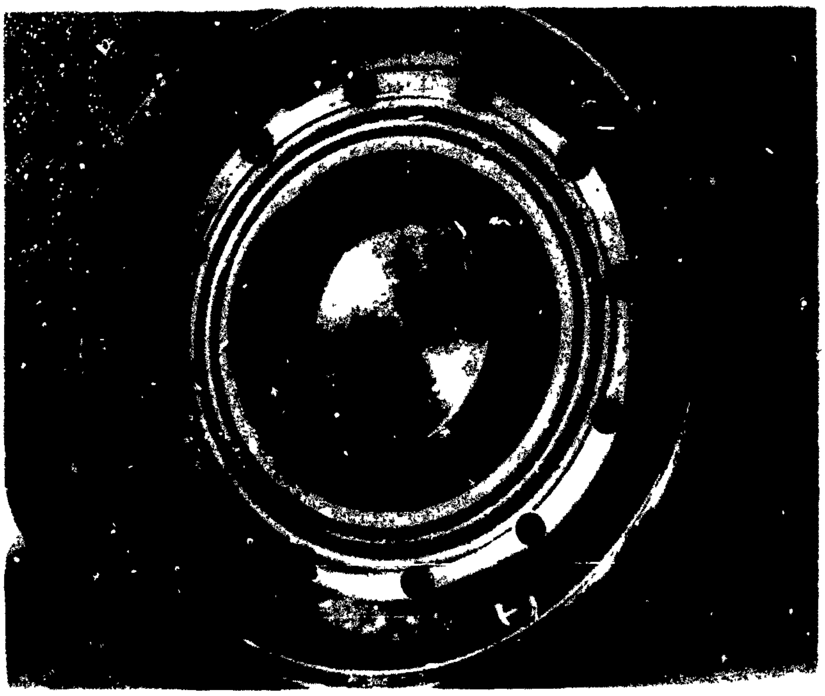


FIGURE 30 CATHODE AND ANODE IN TUBE BODY BEFORE FINAL SEAL IN-

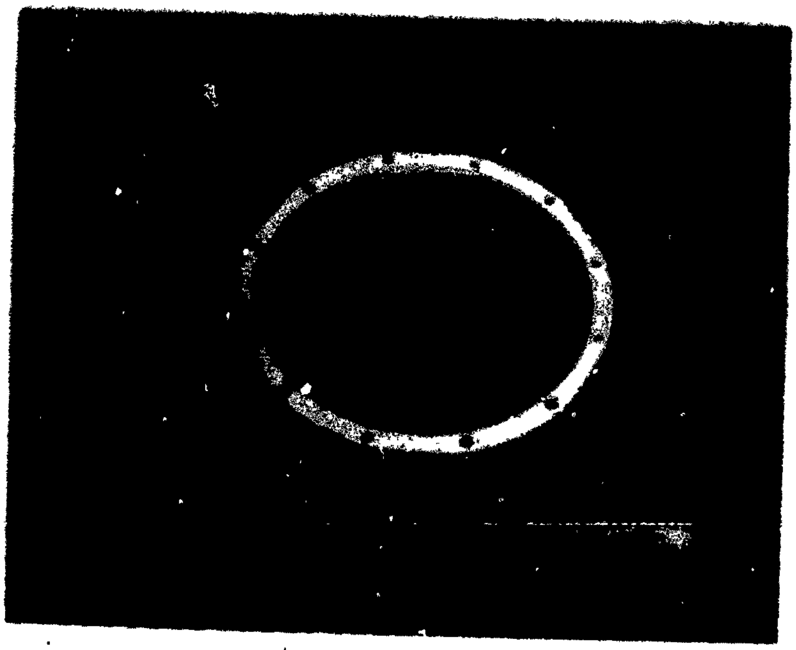


FIGURE 31 UPPER CERAMIC RING WITH CLEARANCE HOLES

FIGURE 32   LOWER CERAMIC RING WITH THREADED HOLES

from the mounting screws to the pole piece. The initial redesign support ceramic was of a one-piece configuration and was capable of withstanding a much higher voltage. Tube D42H, for example, had this type ceramic. The final design, due to its reduced size and weight, required a new ceramic design. Figure 33 shows the arc marks on the lower ceramic with the upper ceramic removed. The arc traces revealed that the length of surface insulation on the ceramic was reduced considerably by the darkened area inside the bolt circle. After an analysis of the breakdown condition and the darkened area, it was concluded that the deposit on the surface of the ceramic was copper which eroded from the anode resonator tips. This erosion, which was minor in nature, is quite common in initial tube starting and aging of magnetrons. However, in this particular design, the combination of the two-piece ceramic and the proximity of the ceramic to the anode resonators was detrimental. Based on the knowledge gained heretofore, the final one-piece ceramic support design was evolved.

On 8 September 1966, an order was placed with the vendor for eight units of the final design with an anticipated delivery date of 2 November 1966. When delivery was not made by December 1966, we confronted the vendor about the problem of fabrication. As it turned out, a problem existed in the initial phases of high temperature firing of the ceramics. The large diameter and thick cross section of ceramic was sagging during the maturing (hardening) stage. As a result, cracks were developing during the cooling cycle. Many attempts were made by the vendor to correct this condition, but with improvements the yield on this operation still did not exceed 50%. As of 24 April 1967, seven units were received on the order placed in November 1966.

In December 1966 when we were confronted with additional delay time on this program because of the procurement of the ceramic support, an alternate design was made which did not require the ceramic support. This new design, shown in Figure 34, was similar to the cathode support structure used in other inverted coaxial magnetrons manufactured at S-F-D laboratories. This design required many more piece parts than the

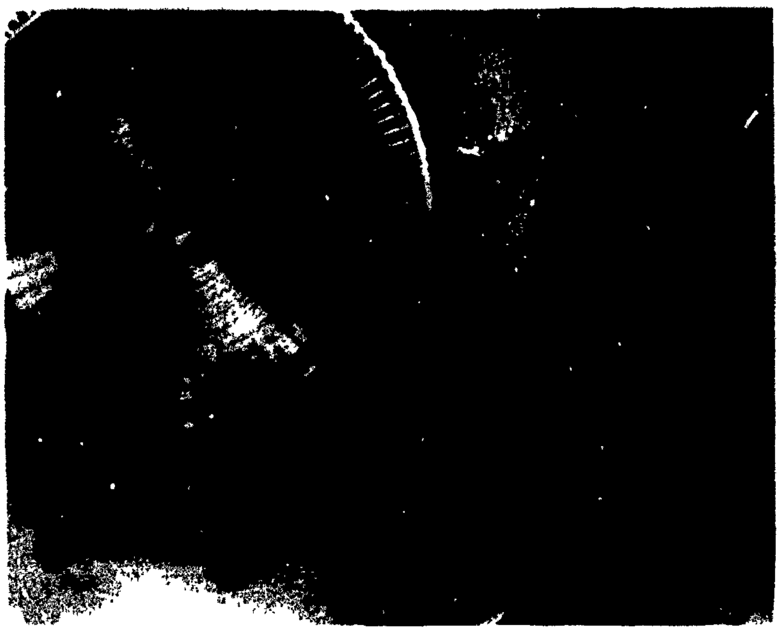


FIGURE 33 ARC MARKS ON LOWER CATHODE CERAMIC SUPPORT WITH UPPER CERAMIC REMOVED

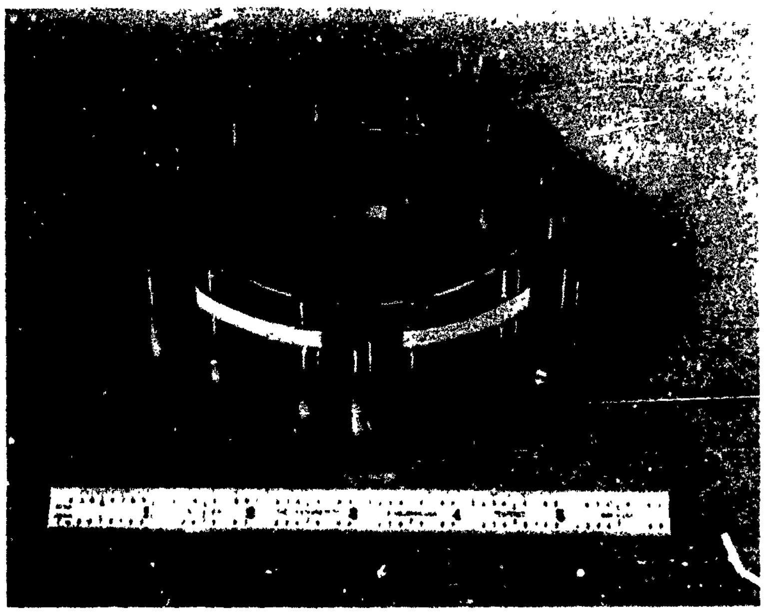


FIGURE 34 ALTERNATE DESIGN OF CATHODE SUPPORT STRUCTURE

one-piece ceramic support, but it was capable of high volume reproduction and reliability. However, since several one-piece ceramic supports became available, this alternate design was installed in a tu tube body for evaluation only. During operation, this tube also showed evidence of cathode motion. Since the contract required tube delivery, the tube was not opened for analysis.

4.1.3 Tuner

The inverted coaxial magnetron tunes, in principle, as simply as a wavemeter. The tuner shaft bearing surfaces consist of a ground, polished, hard chromium surface against a soft copper bearing surface within the vacuum envelope. Thus, the mating surfaces are kept extremely clean throughout tube life, without being affected by environmental changes.

This bearing design, used in other inverted coaxial magnetrons manufactured at S-F-D laboratories, has been tested to 300,000 cycles with no apparent degradation. A conventional low torque tuner drive mechanism was adapted to the tube to provide maximum utility in present and in future systems.

4.2.4 Magnetic Circuit

The factors which determine the flux density requirements in the gap were discussed in section 3.1.2 of this report; and the physical configuration of the magnetic circuit depends on the factors discussed in section 3.2.5, the final pole piece design, and the tube dimensions and configuration. The magnet design is further determined by the permanent magnet material selected and its ability to be case in a configuration which meets the tube packaging requirements and the environmental specifications. Minimum size and weight are also prime considerations.

The magnetic circuit of this tube and of other inverted coaxial magnetrons manufactured at S-F-D laboratories was shifted 90° in position as compared with conventional magnetrons owing to the orientation of the input and output of the tube. As a result, the magnet can be clamped directly to the mounting surface of the system modulator which prevents translating flutter in the magnets to the tube during vibration.

4.2.5 Mode Suppressors

As previously discussed in section 3.1.1.3 of this report, spurious mode competition is dampened by using bands of lossy material. This mode suppressor is essentially a 99% alumina (Al_2O_3) porous body impregnated with sucrose ($C_{12}H_{22}O_{11}$) which is heated in a hydrogen atmosphere to approximately 900°C. At this temperature the sucrose is converted to carbon. The carbonizing process is controlled by recording the weight of the ceramic body before and after processing. The differences in the weights represent the amount of carbon impregnant. A tolerance of weights is established from historical data and this is applied as a manufacturing control on this process.

4.2.6 Cooling Provisions

To achieve the cooling characteristics described earlier in this report, a liquid cooling manifold was adapted to the external surface of the anode. Two quick-disconnect type liquid pressure fittings were mounted on the manifold to permit a circulatory flow of liquid around the anode cooling vanes.

This cooling device which was demountable and compact in design also served as a mounting surface for the tuner mechanism. This prevented any seizure through heating of the tuner parts if any extended tuner cycling was desired.

4.2.7 Packaging of the Complete Tube

Figure 35 shows the final packaged design of the SFD-328 as viewed from the cooling manifold and tuner end. The high voltage and heater input stem extends through the mounting plate which is sealed

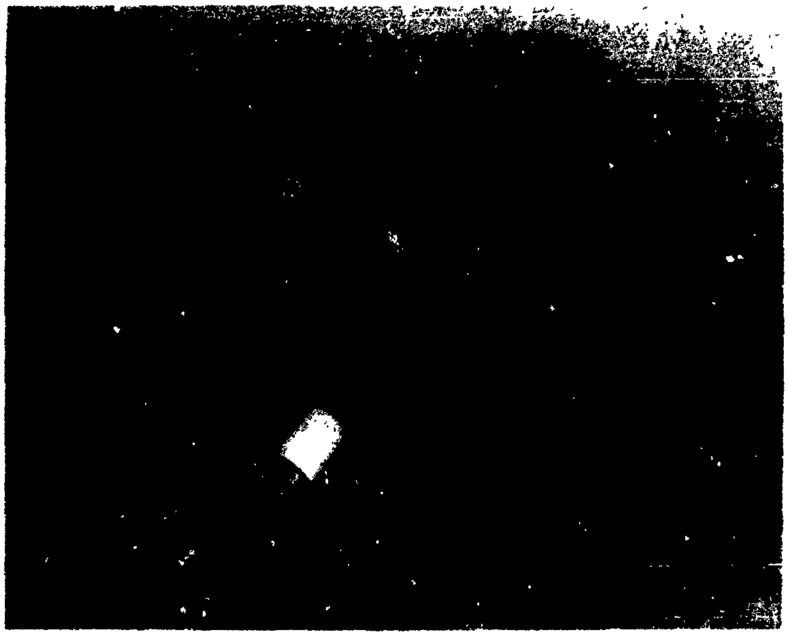


FIGURE 35 SFD-328 FINAL DESIGN VIEWED FROM TUNER END

for pressurization. Figure 36 shows the final design SFD-328 as viewed from the output end. The ceramic output window extends 180° from the tuner end and is sealed for pressurization. The output connector is a modified UG-51/U cover flange.

An outline drawing of the SFD-328 is shown in Figure 37.

4.2.8 Parts and Sub-assembly Evaluation

4.2.8.1 Output

The physical parameters for the electrical design were determined in an intermediate tube structure, which was made for the convenience of design changes. A program of size and weight reduction was then initiated.

Figure 38 shows the final output cover assembly as compared to the intermediate output cover assembly. A weight reduction of 38% was realized by adding the series of holes and by reducing the diameter of the cover plate. Due to the large diameter of the copper cover plate (approximately 6") which was brazed to the steel pole piece, the outer diameter of the cover plate became distorted. Therefore, all critical dimensions were machined after the braze had been completed to insure proper alignment at tube assembly.

Figure 39 shows the output cover assembly mounted on the intermediate tube structure and the reduced final design structure.

4.2.8.2 Body Assembly

In conjunction with the size and weight reduction of the intermediate tube structure, the finalized body assembly was reduced in weight by 55%. This weight reduction resulted from a 1.250" reduction in the body diameter and a 1" reduction in depth. A comparison of the two body assemblies is shown in Figure 40.

The intermediate body design was cooled by liquid flowing through a channeled cavity in the lower face of the body shell.

FIGURE 36 SFD-328 FINAL DESIGN VIEWED FROM OUTPUT END

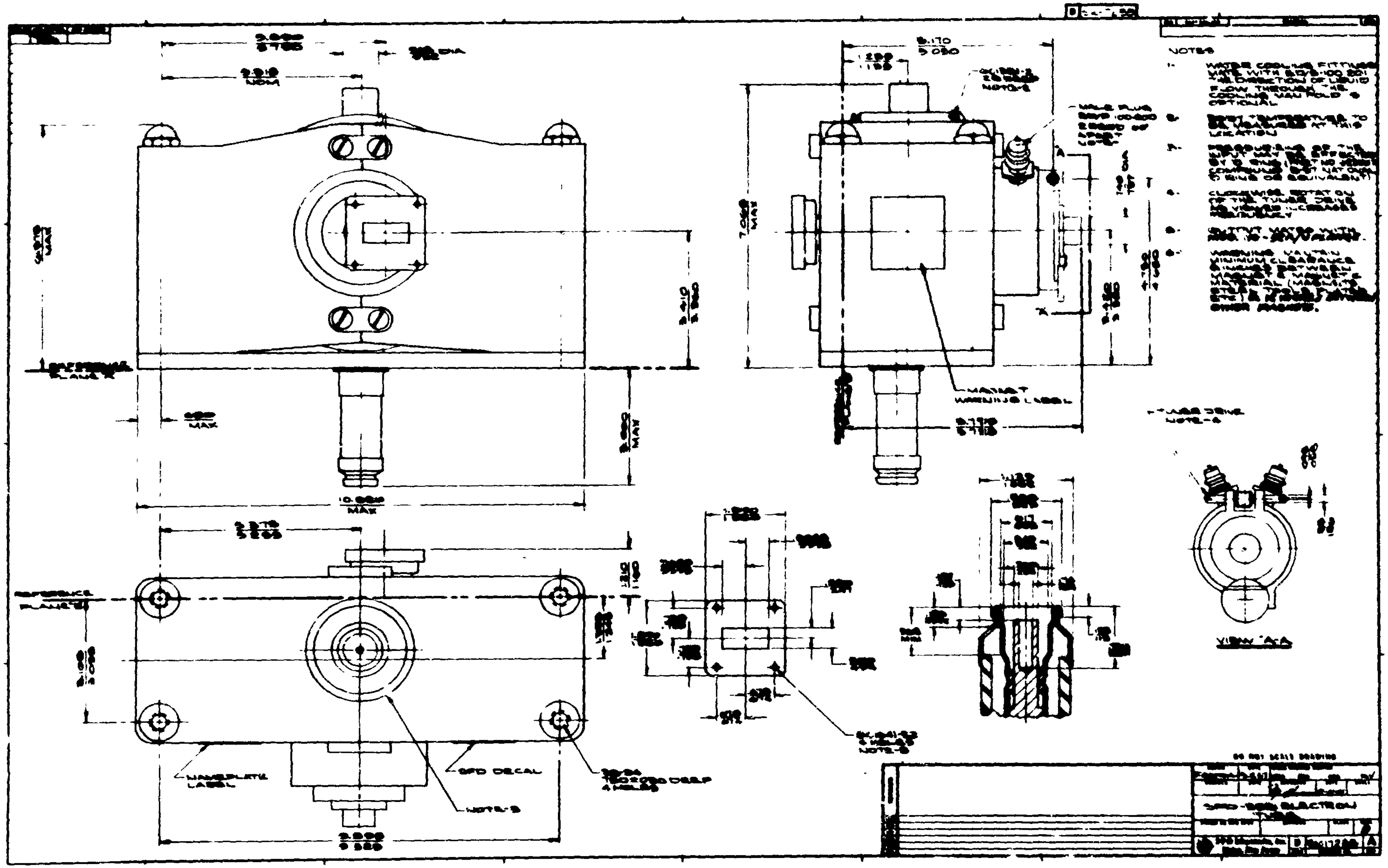


FIGURE 37 SFD-328 ELECTRON TUBE DRAWING

FIGURE 38 COMPARISON OF OUTPUT COVER ASSEMBLY BEFORE AND AFTER SIZE AND WEIGHT REDUCTION

FIGURE 39 OUTPUT COVER ASSEMBLY MOUNTED ON INTERMEDIATE DESIGN STRUCTURE AND ON THE REDUCED FINAL DESIGN STRUCTURE

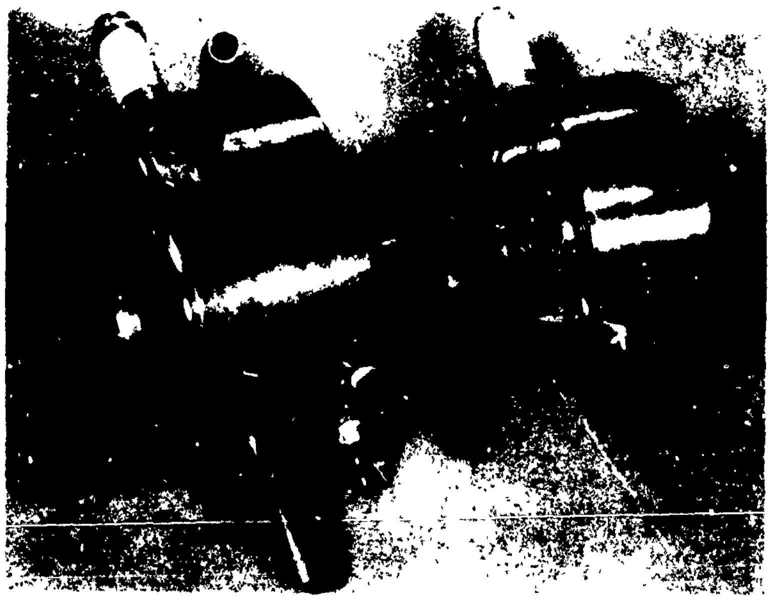


FIGURE 40 COMPARISON OF BODY ASSEMBLY BEFORE AND AFTER SIZE AND WEIGHT REDUCTION

Mounting the cooling manifold directly on the anode extremity increased the efficiency of the cooling principle and accounted for a considerable reduction in weight.

4.2.8.3 Input

A ceramic input assembly was selected for this tube owing to the advantages of ceramic over glass in this application. These advantages were as follows:

1. greater resistance to thermal shock
2. lower dielectric loss at high frequencies
3. higher bake out temperatures which increase shelf life and promote long life
4. ease of assembly with higher reliability and less shrinkage
5. greater strength.

The ceramic input assembly used in the final design of the SFD-328 was developed and used by S-F-D laboratories on another inverted coaxial magnetron manufacturing methods program, Contract AF 33(657)-9970. Figure 41 shows the input assembly on the final design tube after bake out.

4.2.8.4 Mounting Provisions

The mounting plate size and shape were determined by the magnet configuration and the environmental conditions to be imposed on the tube structure. The material selected for the plate was cupro-nickel which has good strength and is non-corrosive. Figure 35 showed the mounting plate on the completed package. The O-ring groove on the mounting surface provided a means of sealing the tube to the system for pressurization of the input. Four threaded bushings were inserted through the mounting plate to clamp the tube to the system.

FIGURE 41 INPUT ASSEMBLY OF FINAL DESIGN SFD-328 AFTER BAKE OUT

5.0 EVALUATION OF FINAL DESIGN AND PRODUCTION TUBES

The objective of the final design phase of this program was to write a specification which reflected the electrical capabilities of the tubes built. The sections which follow describe, in detail, the technical information obtained from this effort. Also included are discussions on four tubes which were evaluated during the manufacturing phase of the program. The test results for all operable tubes are given in Table II. The final specification is included in Appendix I.

5.1 Technical Information

5.1.1 Pulse Input Requirements

All of the X-band ICEM magnetrons tested during the initial and final stages of the program performed better when operated under conditions different from those initially set down in the objective specification. Operation at 50 amperes of peak current with the peak input voltage between 26 kv and 30 kv was the input requirement set down in the objective specification. Tests performed under these conditions yielded poorer pushing characteristics than could be obtained when the peak current was increased to the 60 ampere region. Since the operation at 60 amperes peak current with the original peak voltage limits would increase the input power to 1.8 Mw maximum, a corresponding reduction in peak input voltage has been included.

The final specification has been written to require 60 amperes of peak input current with the peak input voltage required to be 23 kv to 27 kv. Maximum input power under these conditions is 1620 kw as compared to the 1500 kw indicated on the original objective specification.

A further change in pulse input characteristics in terms of rate of rise of voltage was also required to permit operation under

TABLE II

SUMMARY OF TEST RESULTS FOR FOUR PRODUCTION TUBES

Test	Conditions	Limits Min	Limits Max	Units	Tube Serial No. B13I	C164I	D14I	H53I
Dimensions		-	-	-	--	--	--	--
Pressurization		45	-	psia	Passed	Passed	Passed	Passed
Tuner Torque		-	15	in-oz	4	5	10	--
Heater Current	$E_f = 23$ v	8	10	amps	8.8	9.6	9.2	9.1
Warm-up Time		-	300	sec	Passed	Passed	Passed	Passed
Cathode-anode Capacitance		55	85	pf	70	71	73	--
Operating Tests	Osc. 1							
	t_{pc}			μsec	2.25	2.4	2.3	2.3
	du = 0.001 I_b = 60 ma dc							
Pulse Voltage	F_1	23	27	kv	24.5	24.6	24.8	24.9
	F_3				25.2	25.7	25.7	25.4
	F_5				25.6	26.0	26.3	25.7
Power Output	F_1	400	-	w	422	462	450	378
	F_3				489	515	483	462
	F_5				460	437	415	391
RF Bandwidth	F_1	-	$2.4/t_{pc}$	MHz	0.5	0.57	0.43	0.6
	F_3				0.5	0.65	0.50	0.6
	F_5				0.5	0.57	0.40	0.6
Spectrum Minor Lobes	F_1	8	-	db	13.5	12	12	10.5
	F_3				11.0	11	11	11.0
	F_5				11.5	14	12	11.0
Stability	F_1	-	0.5	%	0.0	0.0	0.004	0.0
	F_3				0.0	0.0	0.020	0.0
	F_5				0.0	0.0	0.004	0.0
Tunable Frequency		F_5+25	F_1-25	MHz	Passed	Passed	Passed	Passed
Pushing Factor	F_1	-	0.1	MHz/amp	0.05	0.05	0.01	0.1
	F_5				0.01	0.05	0.03	0.1
Pulling Factor	F_1	-	6.0	MHz	2.0	2.3	2.1	2.0
	F_5				3.0	2.9	3.5	3.5

conditions yielding good magnetron performance. The rate of rise of voltage has been reduced from 150 kv/μsec to 100 kv/μsec. Operation at 150 kv/μsec was obtained on two final design tubes, but was not as stable as that obtained when the rate of rise of voltage was reduced to 100 kv/μsec. The specification has been written requiring 100 kv/μsec minimum for the input test requirement.

5.1.2 Power Output

Two final design tubes were tuned and operated over the 8.6 GHz to 9.6 GHz tuning range. Output power as a function of frequency for these tubes under the final specification input conditions is shown in Figures 42 and 43. Both tubes generated 500 kw of peak output power over approximately 50% of the required tuning range. Power output over the complete tuning range remained well above 400 kw. Based upon this performance, the specification is written to place a 400 kw minimum output power requirement over the 8.6 GHz to 9.6 GHz range. Additionally, no damage or degradation in electrical performance was observed when the tuning range was exceeded by 25 MHz at each end of the frequency band. Such a capability is needed to insure setting the tube frequency to the extreme band edge frequencies within normal frequency tolerances.

Three production tubes - D14I, D223I and H53I - were operated under similar conditions. Power curves for these three tubes are shown in Figure 44 and agree closely with those for the two final design tubes.

An undesirable feature of this magnetron, however, is its inability to withstand sudden application of high voltage, for operation at high average power. This can be explained as follows.

The ICEM anode, which is inside the cathode, expands toward the cathode when heated, causing a reduction in operating voltage. If the tube is stabilized to operate at 1.5 kw input, with an operating

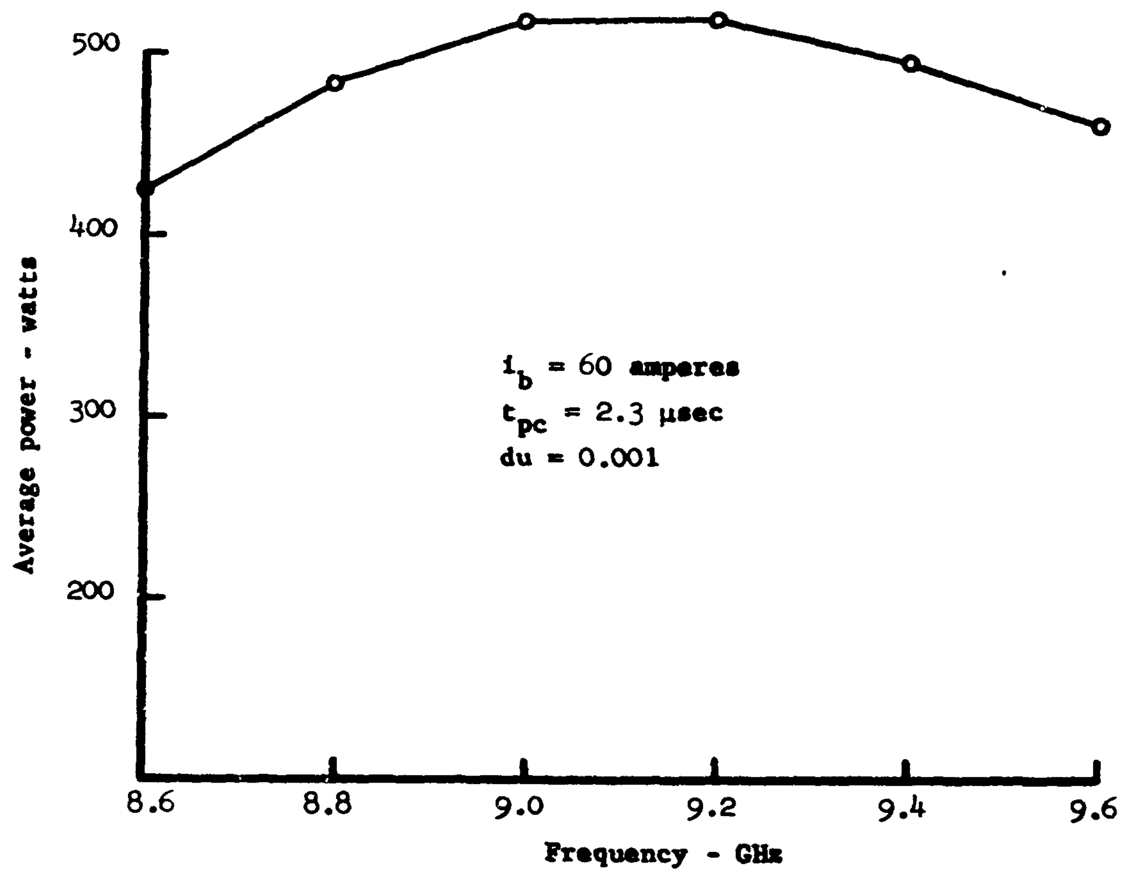


FIGURE 42 POWER OUTPUT VERSUS FREQUENCY CHARACTERISTIC FOR TUBE B13I

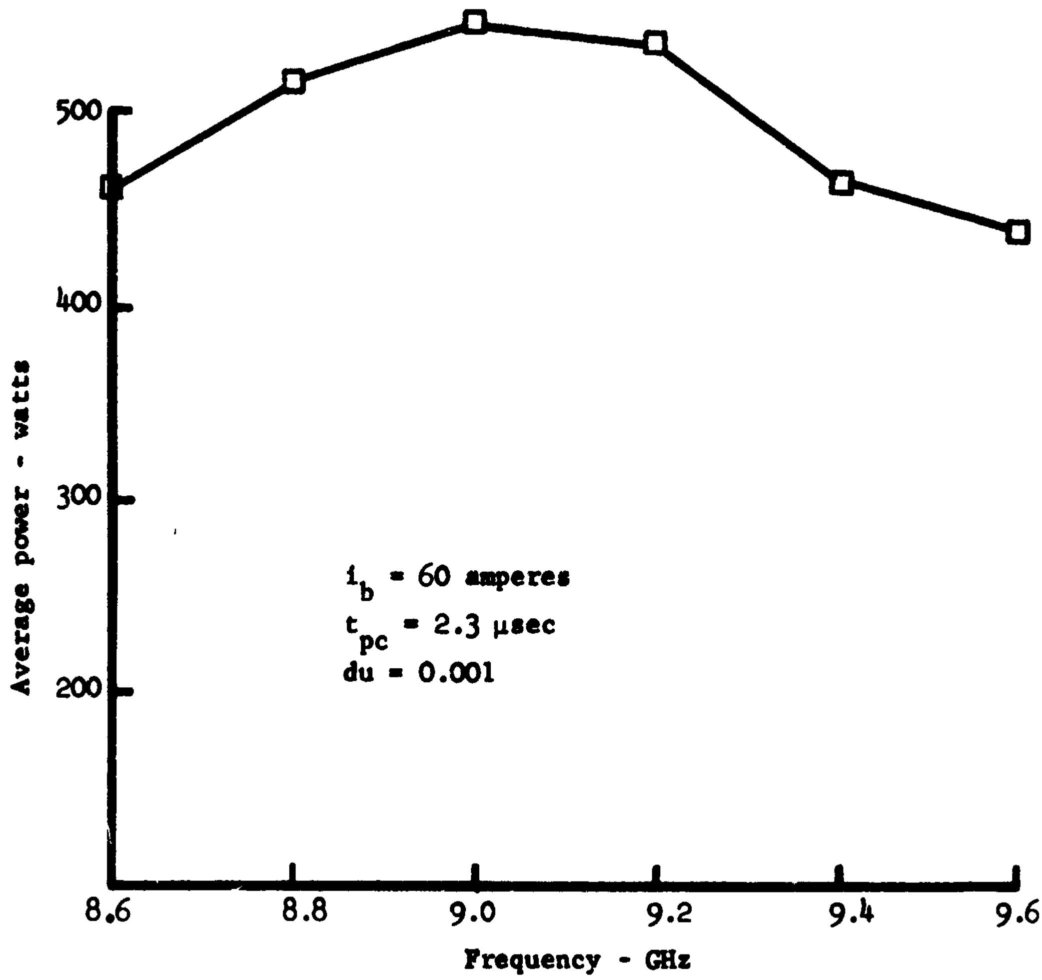


FIGURE 43 POWER OUTPUT VERSUS FREQUENCY CHARACTERISTIC FOR TUBE C164I

	Curve A	Curve B	Curve C	
Tube	D14I	D223I	H53I	
i_b	60	60	60	amps
du	0.001	0.001	0.001	
e_{py}	≈26	25.5	25	kv
t_{pc}	2.3	2.3	2.3	μsec

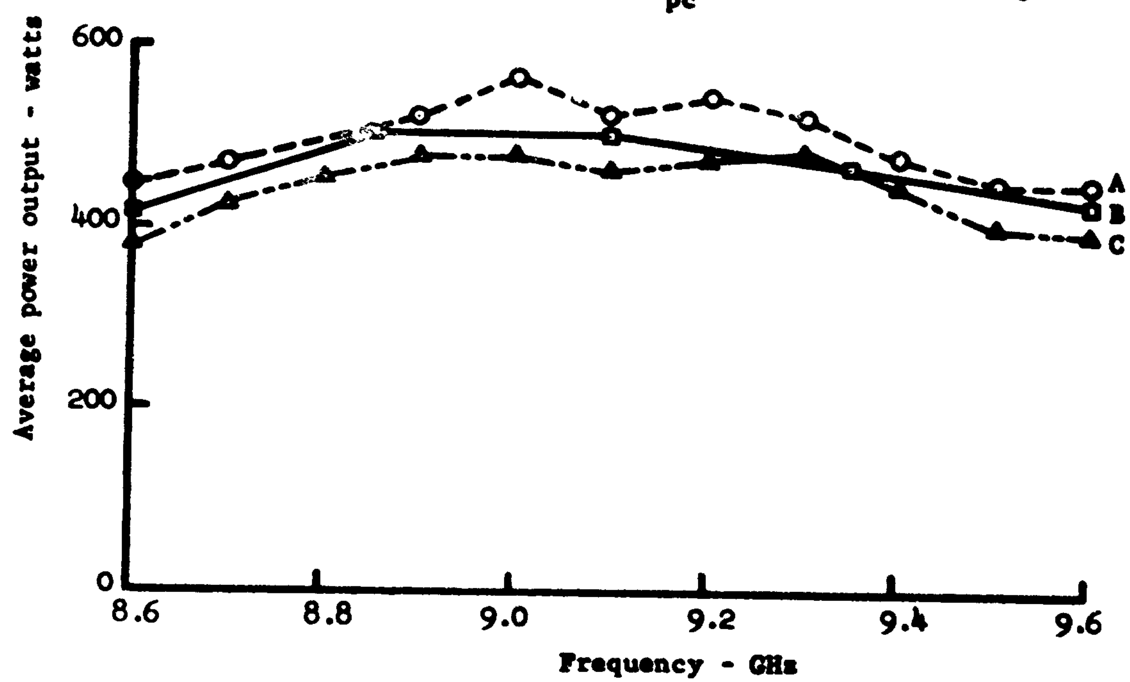


FIGURE 44 POWER CHARACTERISTICS OF THREE PRODUCTION TUBES

voltage, e_{py}, of say 26 kv, then the cathode-to-anode spacing is fixed at g. When the tube is allowed to cool, the cathode-anode spacing increases to $(g + \Delta g)$, and if voltage is applied to reach the original operating current, the voltage required is $(e_{py} + \Delta e_{py})$. With the present specification power conditions, Δe_{py} can be as much as 5-7 kv. This increased voltage can cause severe internal and external arcing. and damage to both the tube and the modulator.

An associated problem is that the tube is unable to operate over a range of average power inputs with constant peak V-I characteristics.

Tests on final design tubes at higher-than-specified input conditions were performed on the test electromagnet. With the magnetic field increased, operation at voltages up to 30 kv was obtained. At the higher levels of input voltage, it was determined that increasingly higher levels of peak input current were required to achieve good magnetron performance. Such a combination of both higher peak input voltage and peak input current was required to permit operation of the SFD-328 at 1 Mw of peak power output. Average power input was limited to 1.8 kw due to the design of the anode cooling system. A somewhat larger cooling manifold than employed on the final design SFD-328 would be required to permit operation at 1 Mw of output power at a 0.001 duty cycle. Since the specification is written around the lower level of average power operation, such a limitation in average power handling capability is to be expected. Minor modifications in the cooling manifold region of the tube would be required to provide higher dissipation capabilities.

5.1.3 Pushing and Pulling

Two operating parameters of prime importance in determining the quality of an oscillator require the measurement of frequency as a function of the variation of either input or output conditions. In the case of a magnetron, the input variation effect on frequency is called pushing. Magnetron peak current variations are translated into frequency shifts as a result of electronic tuning. The stabilizing effect of the TE_{011} mode cavity is responsible in the ICEM magnetron for reducing the pushing factor to very low levels. The pushing factor can be related to spectrum quality, with low pushing factors yielding the best spectrum quality. In the case of the SFD-328, the pushing factors are typically low in terms of megahertz per ampere. Measurements across the tuning range around the 60 ampere operating point yield values of 0.05 MHz/amp.

Magnetron frequency stability as a function of load impedance variation is defined by the pulling factor. It is measured by determining the maximum frequency deviation produced by a 0.2 voltage reflection coefficient varied through 360° of electrical phase shift. The ICEM magnetron, because of its TE_{011} mode stabilizing cavity, produced pulling factors of only a fraction of those realized when using conventional magnetrons. Measurements on the SFD-328 produced pulling factors well below the specification maximum, as shown in Table II.

5.1.4 Spectrum Quality

Two test parameters are used to define the quality of the spectrum resulting from the pulsed output of a magnetron. The first of these parameters is the RF bandwidth normally expressed as a function of current pulse length. This measurement requires that the frequency width of the major lobe of the spectrum be determined at a level of 6 db below the peak value of the major lobe. Additionally when the spectrum is viewed, a mismatch is presented to the tube output system with a magnitude of 1.5:1 VSWR and its phase adjusted to produce maximum spectrum degradation. Under these conditions of load mismatch, the width of the major lobe is measured in frequency units. Since the pulse length used determines the theoretical bandwidth of the resultant spectrum, the specification was written to relate the bandwidth limit to the applied current pulse width. Measurements of this parameter obtained on the SFD-328 at 2.3 μsec current pulse length yielded bandwidth measurements of approximately 0.6 MHz. Since the current pulse width was 2.3 μsec, the bandwidth may be stated to be $1.4/t_{pc}$. This value of bandwidth is well within the $2.5/t_{pc}$ limit in the specification.

The second test parameter used to determine spectrum quality is the minor lobe ratio. The ideal spectrum resulting from rectangular pulse amplitude modulation of an oscillator would be a symmetrical spectrum with side lobes of equal amplitude on each side of the carrier frequency. However since the pulse applied is trapezoidal, having finite rise and fall times, the effects of pushing or frequency modulation characteristics of the magnetron modify the ideal spectrum so as to produce imbalance in the side lobes. Measurement of the amplitude of the side lobes relative to the amplitude of the major lobes provides a means of placing controls on the pushing characteristics of the magnetron. Power ratios of the major to minor lobe amplitudes, expressed in decibels, are used as specification limits. As expected from the low pushing factors measured on the SFD-328, the side lobe ratios are very high. Minimum values of 10 db, including the effects of output mismatch, were measured across the frequency tuning range.

5.1.5 Stability

Stability of a magnetron is determined by comparing the energy content of each pulse with the average of a series of past occurring good pulses. When a pulse for any reason contains less than 70% of the energy of the normal pulse, it is considered to be missing.

Energy is normally missing from a magnetron output pulse due to arcing or moding effects. Arcing is the cause of very few missing pulses in a well designed and thoroughly aged magnetron. Once aged, the SFD-328, because of its conservative design in terms of internal spacings and materials, is relatively free from arcing. Moding effects on the SFD-328 have not been of the type which will yield missing pulse counts. At rates of rise higher than 100 kv/µsec, some slight increase in delay of starting in the π mode has been observed. This delay amounts to less than 1% of the total pulse energy when the rate of rise is increased to 120 kv/µsec. The extremes of delay time occur on less than 1% of the applied pulses. For this reason, the rate of rise of voltage was set at 100 kv/µsec to reduce the leading edge delayed starts to an insignificant value.

5.1.6 Heater Input Power

A magnetron contains only one element which can be considered limited in life time. The dispersion type cathode used in the SFD-328 relies on the arrival of active emitting material at the surface of the cathode from its body to provide primary electron emission. Since a finite amount of active materials are used to impregnate the emitter body, some thought must be given to the use rate of active material as a limiting factor in determining magnetron life. In general for the dispenser type cathode, the higher the temperature of operation, the shorter the primary electronic emission life will be. There is also a lower limit of cathode temperature below which little or no primary emission results. Operation somewhere between the lower limit of temperature and the life limiting upper temperature must be achieved by providing the proper standby and operating heater input power. Experience with the type of cathode used in the SFD-328 dictated a cathode temperature of 850°C to 875°C. By applying 23 volts to the heater of the SFD-328, the required temperature range was reached within

300 seconds. When operation at full specification input levels was attained, reducing the heater input voltage maintained the cathode temperature at the 850°C to 875°C range. Measurement of cathode temperature was made possible by adding a glass window to the exhaust tubulation assembly on all tubes constructed. This viewing window was removed from the tube when the exhaust tubulation was pinched off.

5.1.7 Cooling Characteristics

The final design SFD-328 utilized liquid cooling to dissipate the heat generated as anode dissipation. Use of liquid cooling greatly simplified the design of the final package and also permitted higher cooling efficiency. Water was used as the coolant in all tests performed; however, it is possible to use other types of coolants. For purposes of test evaluation and life testing, a water flow rate of 1.0 gal/min was used. A pressure of 40 psi was required to produce this flow rate through the cooling manifold. Body temperature measurements under these conditions of cooling were 40°C to 50°C.

5.1.8 Cold Test Measurements

As part of the procedure employed to control the characteristics of the SFD-328, a cold test evaluation was required on each tube constructed. Prior to the final operation of sealing the tube, measurements of unloaded Q and circuit efficiency across the 8.6 GHz to 9.6 GHz tuning range were made. If these values did not conform to the limits specified, the tube was not sealed in. Further investigation as to the reasons why the limits were not met was required. When the cause was corrected and the limits were met, the tube would be sealed in. Curves of unloaded Q and circuit efficiency obtained on a typical production tube are shown in Figure 45. The limits for unloaded Q and circuit efficiency are also shown. Verification of these limits was obtained from data accumulated on all tubes constructed. Factors

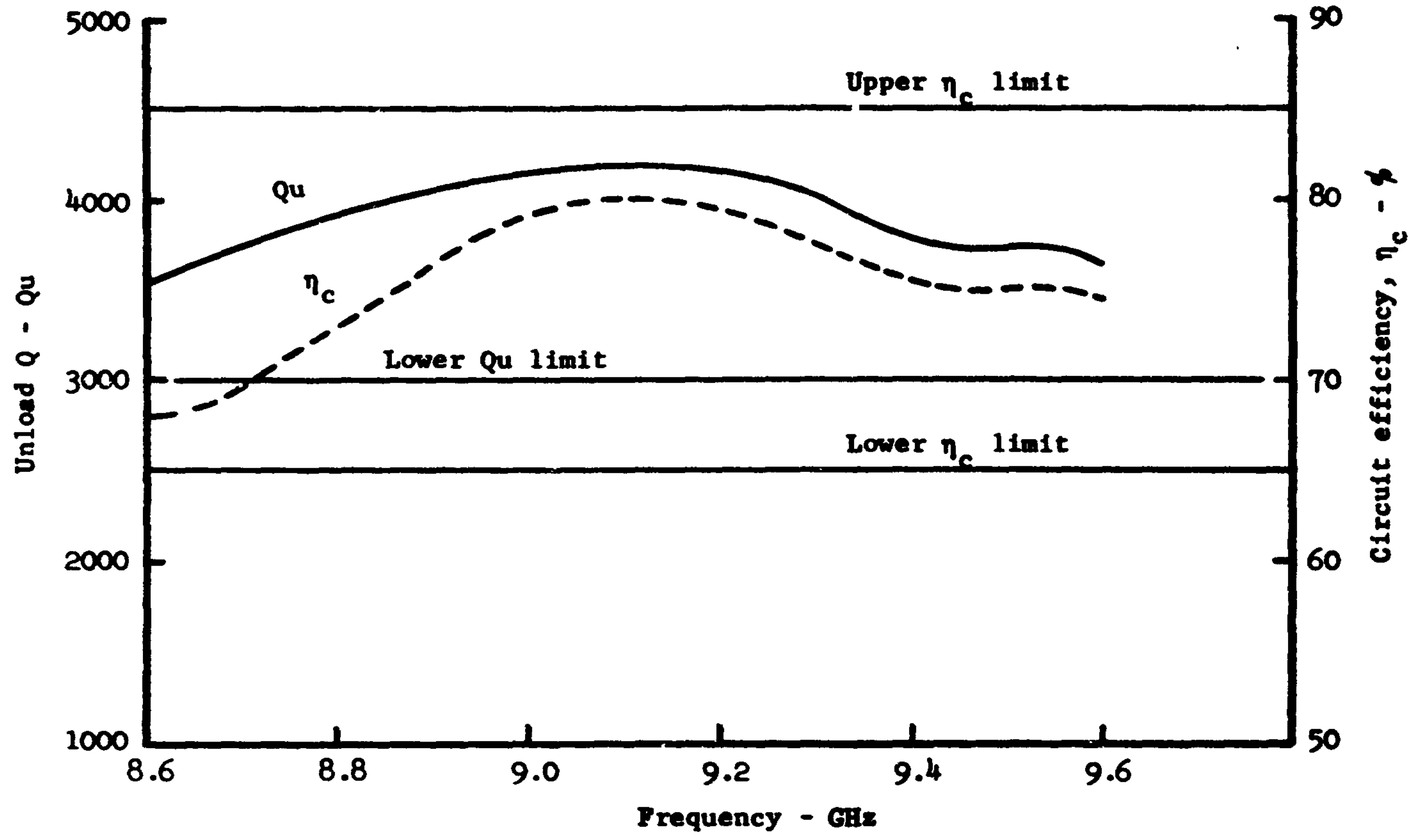


FIGURE 45 TYPICAL COLD TEST RESULTS

influencing these two limits include anode vane symmetry, cavity symmetry, slot mode absorber position, tuning plate tilt, and brazing-induced distortions of the output coupling system. Although each of these areas of the tube was checked mechanically prior to sealing the tube, this final electrical cold test evaluation provided a valuable cross check.

5.2 Life Tests

5.2.1 Heater Cycling Tests

Of primary importance in the evaluation of the SFD-328 was the determination of the cycled life capability of the design. In every area of the design, emphasis was placed on providing capability for long life. Accordingly whenever a possible limitation on life was anticipated, an attempt was made to verify the design employed. One area of the design which fell in this category was the heater. As early as practical in the program, heater-cathode assemblies were subjected to cycling conditions to provide verification of their life capabilities. Cycling tests were performed, in bell jars, on the cathode mounting structure to determine only its dimensional stability. Due to the complexity of the vacuum equipment used for this evaluation, it was not practical to extend the cycling time to provide heater life test data. Heater cycled life data were accumulated with the heater-cathode assembly in the actual tube environment. A total of 2000 heater cycles was applied to tube A9H using a 5 minute ON, 30 minute OFF cycle. Since 1000 cycles of heater use were required during the extended life test, this extra margin of capability was felt to be sufficient. Data obtained on A9H, together with experience gained on extended life Ka-band ICEM magnetrons utilizing a similar heater design, provided sufficient verification of the heater design life capability.

5.2.2 Early Intermittent Life Test

Prior to initiating the extended life test on tubes of the final design, a preliminary evaluation of the life characteristics was required. This early assessment of the life capability of the final design was made using a tube constructed at the end of the final design phase. Tube L35H, which operated above specification power levels across 80% of the required tuning range, was selected to provide the preliminary intermittent life test data. Internally this tube was identical to the production tubes. After operating the tube for test purposes for a period of 30 hours, it was operated on the life test modulator under conditions of input identical to those specified for the extended life tests. Since permanent magnets were not available, the life test was performed using an electromagnet to provide the required magnetic field. Radiate hours were accumulated only during working hours to permit attended operation. The tube was turned off and restarted once or twice each day with the frequency changed once a day. Power output data were recorded once each day. Table III is a summary of the data taken as a function of radiate hours and numbers of cycles. Aside from periodic intervals when the test set was in use for evaluation of new tubes, the life test extended from 4 January 1967 to 21 March 1967. Power output measured daily at 8.6 GHz, 8.9 GHz, and 9.2 GHz is seen to be essentially unchanged throughout the test interval. Variations in power readings shown are due mainly to measurement accuracy and to the difficulty of maintaining the same magnetic field with the electromagnet. Adding the 30 hours and approximately 10 cycles accumulated before the life test started to the tabulated values yields 330 hours of essentially constant operation. Based on these results, it appears that the design is capable of long life. Performance of extended life tests on more than one sample would be required to prove the full life capability of the design.

TABLE III

LIFE TEST SUMMARY FOR SFD-328 X-BAND ICEM MAGNETRON, SERIAL No. L35H

Date	Cumulative Radiate Hours	Cumulative Cycles	Power Output - watts 8.6 GHz	8.9 GHz	9.2 GHz
4 Jan 1967	0.0	0	405	473	450
4 Jan 1967	3.6	1	405	467	444
5 Jan 1967		2	418	471	459
5 Jan 1967	11.3	3	387	444	433
6 Jan 1967		4	397	461	439
6 Jan 1967	16.5	5	400	461	439
9 Jan 1967		6	400	450	435
9 Jan 1967	25.0	7	395	455	433
10 Jan 1967		8	394	457	439
10 Jan 1967	32.2	9	400	450	444
11 Jan 1967		10	389	455	445
11 Jan 1967	38.8	11	389	450	433
12 Jan 1967	46.3	12	388	462	456
13 Jan 1967	53.4	13	394	469	456
16 Jan 1967	55.3	14	400	462	444
17 Jan 1967	63.2	15	386	479	450
18 Jan 1967	71.4	17	419	487	469
20 Jan 1967	75.1	19	406	469	463
23 Jan 1967	82.5	21	406	469	456
24 Jan 1967	89.2	23	395	455	437
25 Jan 1967	97.9	24	405	462	450
26 Jan 1967	104.0	26	400	475	450
27 Jan 1967	111.8	28	405	462	459
30 Jan 1967	118.0	29	400	450	444
1 Feb 1967	134.5	32	405	455	444
13 Feb 1967	167.6	50	419	469	469
14 Feb 1967	176.2	51	425	494	494
15 Feb 1967	184.4	52	418	475	475
16 Feb 1967	192.0	53	431	487	481
17 Feb 1967	200.2	54	412	456	462
23 Feb 1967	220.5	58	412	456	483
24 Feb 1967	228.6	59	406	438	469
27 Feb 1967	229.6	60	419	456	469
28 Feb 1967	244.9	61	425	462	494
9 Mar 1967	251.7	62	422	472	467
10 Mar 1967	259.3	63	400	421	464
15 Mar 1967	270.8	65	417	445	472
16 Mar 1967	278.5	66	400	444	462
17 Mar 1967	286.0	67	394	431	438
21 Mar 1967	301.2	69	404	432	454

End of test

5.2.3 Final Design Life Test

Extended life testing was begun during May 1967 on tube D14I. Tube D14I was the first tube built during the production phase of the program, and met the requirements of the final tube specification sheet. The initial test results were given in Table II.

For the first 200 hours of life, the modulator was run only during the day and was shut off in the evening. Thereafter, the tube was operated overnight for maximum high voltage, on-time accumulation. Many difficulties were encountered, however, in trying to obtain 24 hour operation. Very often, the modulator would have turned itself off before the morning and hours of operation would be lost. In the process of obtaining more reliable operation, all of the major modulator components were replaced over a period of time. At this time, reliability has improved, but the modulator still shuts down occasionally for no apparent reason.

Magnetron power output variations during this life test are given in Figure 46. The rapid drop in power during the first 200 hours of life is believed to result from cathode radial position variations. This is substantiated by the fact that the voltage (e_{py}) decreased during the time of the most rapid power fall off. At the present time voltage fluctuations still occur, but they are not of the original magnitude. This indicates that some movement is still taking place, but the movement is not cumulative in its magnitude and direction.

Of the four tubes built during the production phase, two were early failures due to internal mechanical fractures of absorbers and cathode. The fourth tube, H53I, was not available until August 1967, and it also had cathode movement problems.

At the present rate of accumulation of high voltage hours, it is expected that the 5000 hour point will be reached during July 1968. A supplement to this report will then be issued containing the complete life test history.

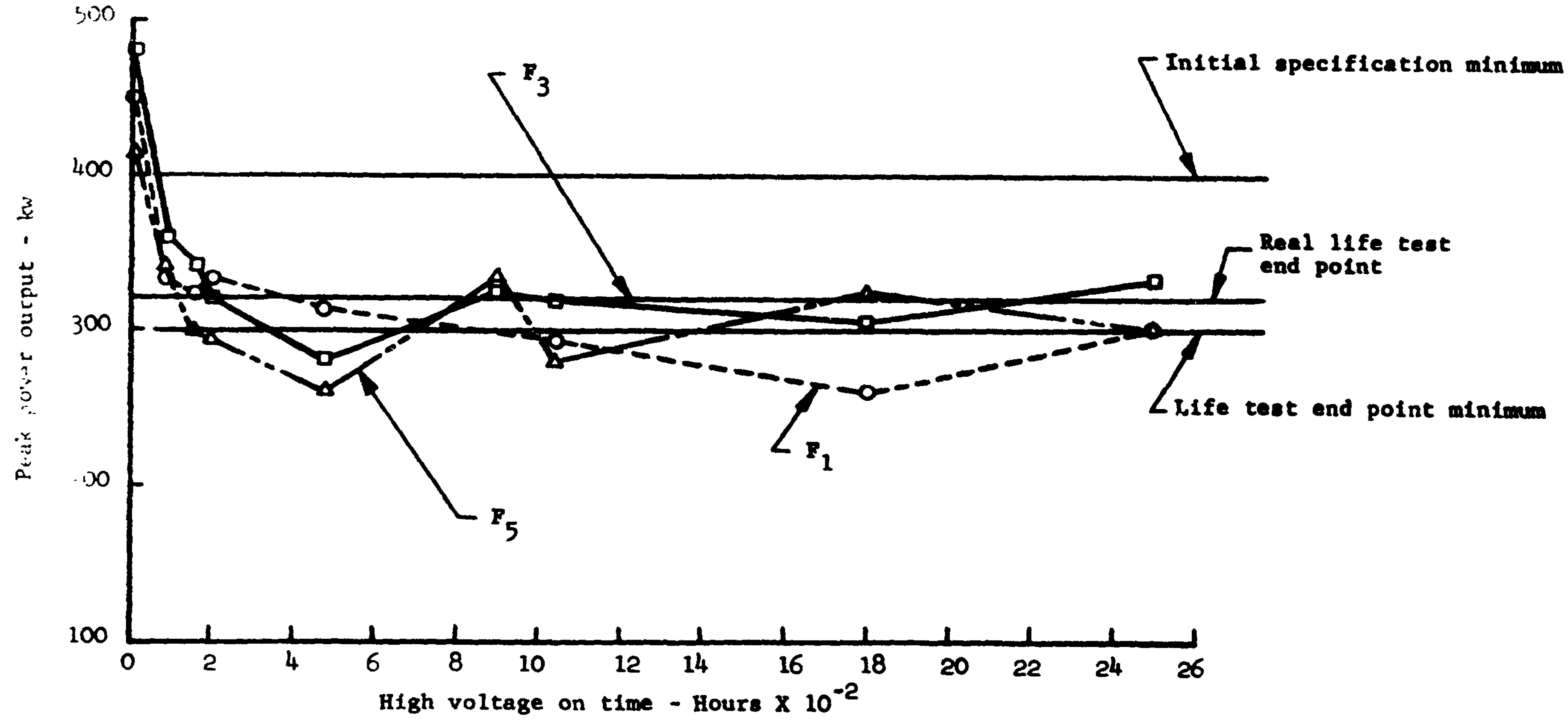


FIGURE 46 LIFE TEST POWER CURVE

5.3 Test Equipment

5.3.1 Cold Test Equipment

Evaluation of the X-band ICEM design required the measurement of resonant cavity Q factors. Q factors are derived from the investigation of the cavity impedance in the vicinity of resonance by use of a swept frequency reflectometer. Use of this technique permits the rapid and accurate determination of unloaded Q, external Q, loaded Q, and circuit efficiency.

The cold test set used to evaluate the X-band ICEM magnetron Q factors is shown schematically in Figure 47. A klystron which is both mechanically and electronically tunable generates the necessary swept frequency across the 8.6 GHz to 9.6 GHz tuning band. Samples of the incident and reflected power are successively displayed on an oscilloscope. A sliding short circuit provides a reference for a adjusting the magnitudes of the incident and reflected signals. Frequency and bandwidth readings are taken using a precision wavemeter and a precision attenuator with the cavity connected to the test set. All of the required Q factors can be calculated using methods similar to those discussed by E. D. Reed (Ref. 4).

5.3.2 Hot Test Equipment

The test set used to measure the operating parameters of the X-band ICEM magnetron is shown schematically in Figure 48. The pulse input voltage is provided by a line type modulator which is instrumented to measure all pertinent magnetron input parameters. Metering is provided to indicate average input current, peak input voltage, heater voltage, and heater current. Output power is coupled from the tube to a waveguide load system which is arranged to permit the measurement of average output power, output frequency, spectrum quality, and detected RF pulse output.

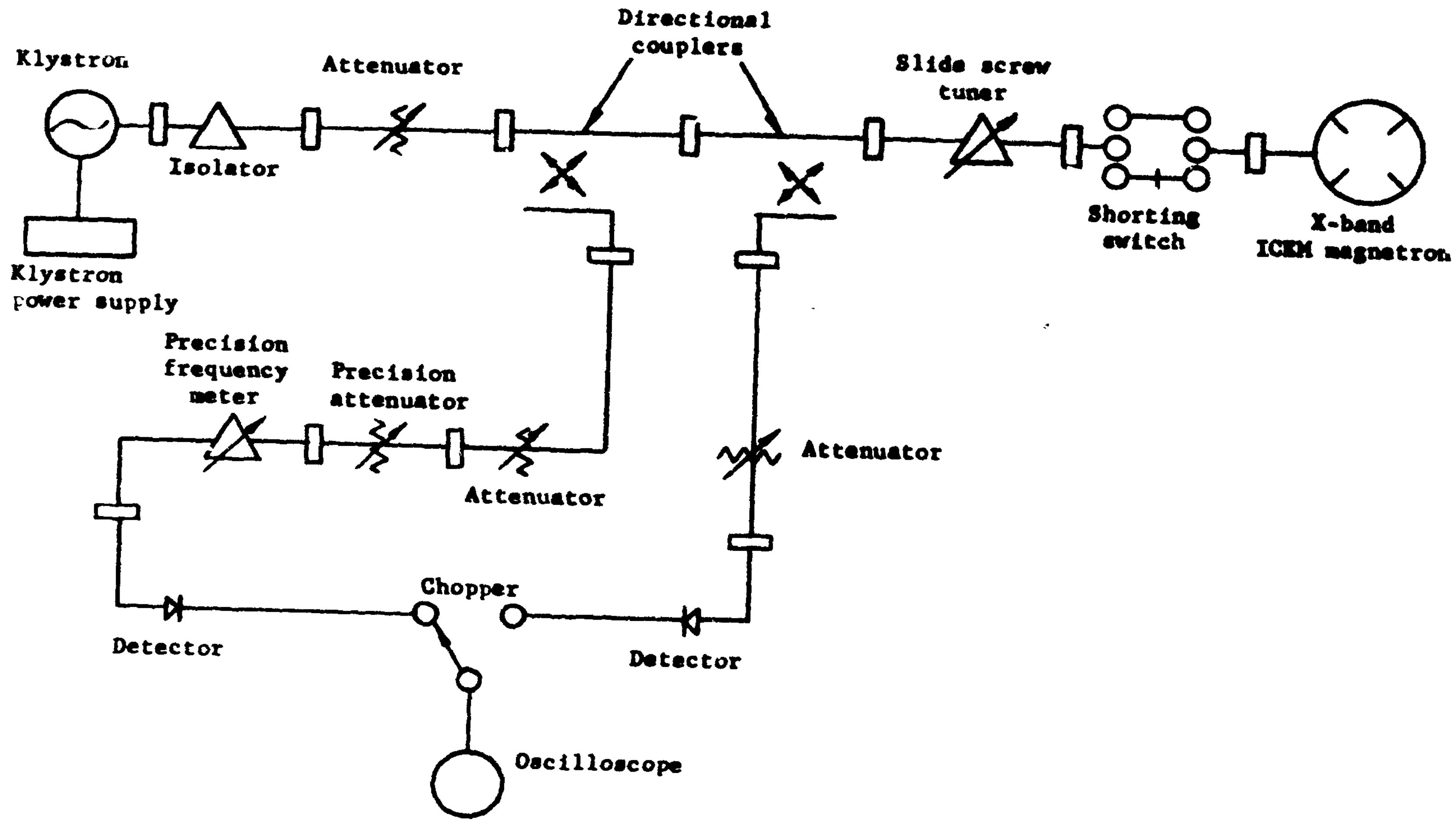


FIGURE 47 SCHEMATIC OF X-BAND COLD TEST STATION

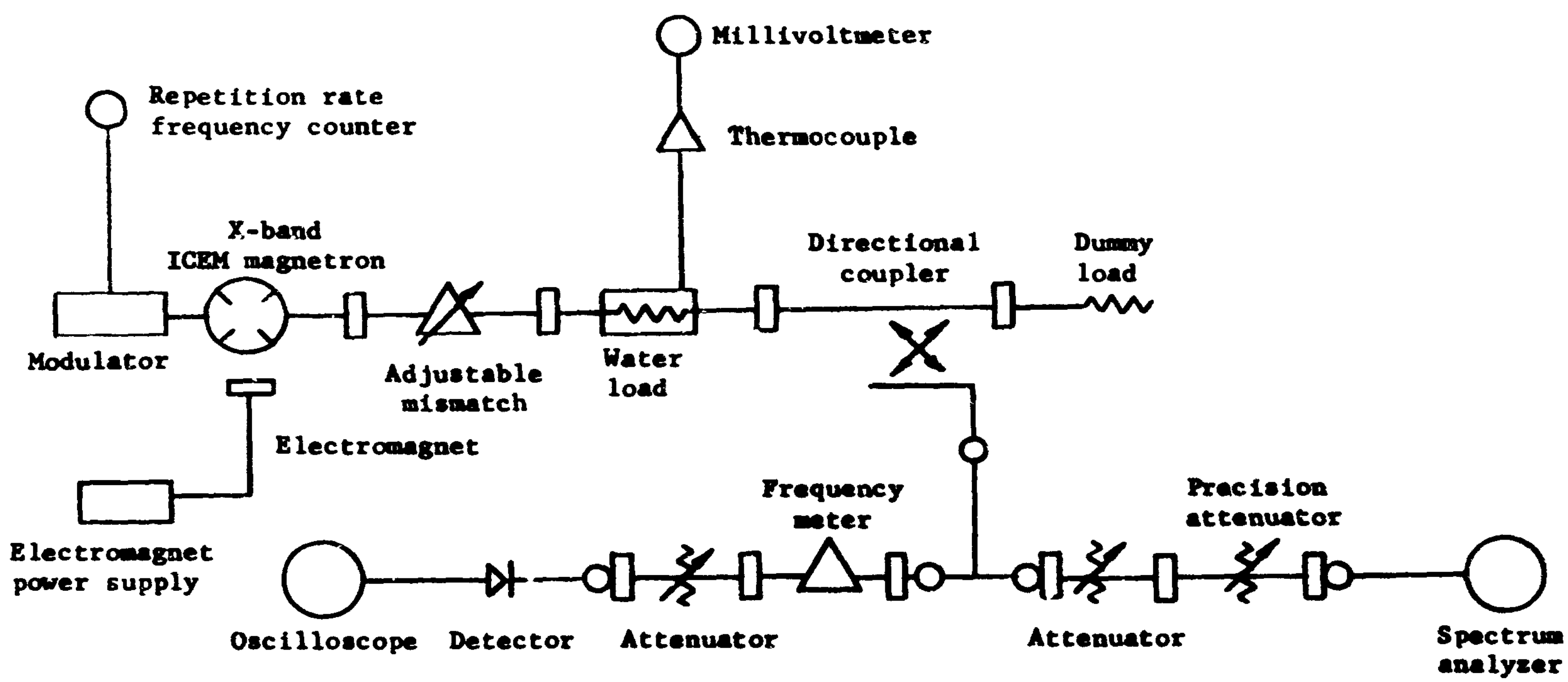


FIGURE 48 SCHEMATIC OF X-BAND HOT TEST STATION

Two complete test sets were provided which are used for evaluating new tubes as well as for performing the life tests. A photograph of both test sets is shown in Figure 49. Provisions were made for unattended operation so that the maximum amount of operating hours could be accumulated in the time period allocated for the life test phase of the program. Due to the danger of leaks and pressure changes, a dry load had to be used during life test. Power output checks thus requires substitution of a water load.

5.4 Pilot Production Line

The pilot assembly line utilized throughout this program was limited in size because of the small quantity of tubes built. The capability of this line and the supporting facilities are shown in Figures 50 to 56.

The pilot line is located in a clean room which is air conditioned, has controlled humidity, and is electronically dust filtered. Special lint-free laboratory coats are worn by all personnel in this area. Within this clean room area are several separate rooms which contain supporting facilities such as heliarc welding, vacuum RF brazing, vacuum firing, and chemical cleaning. These separate rooms are located so as to minimize the possibility of contaminating the devices.

Other facilities which support the assembly pilot line are located outside the clean room and are shown in Figures 57 through 59.

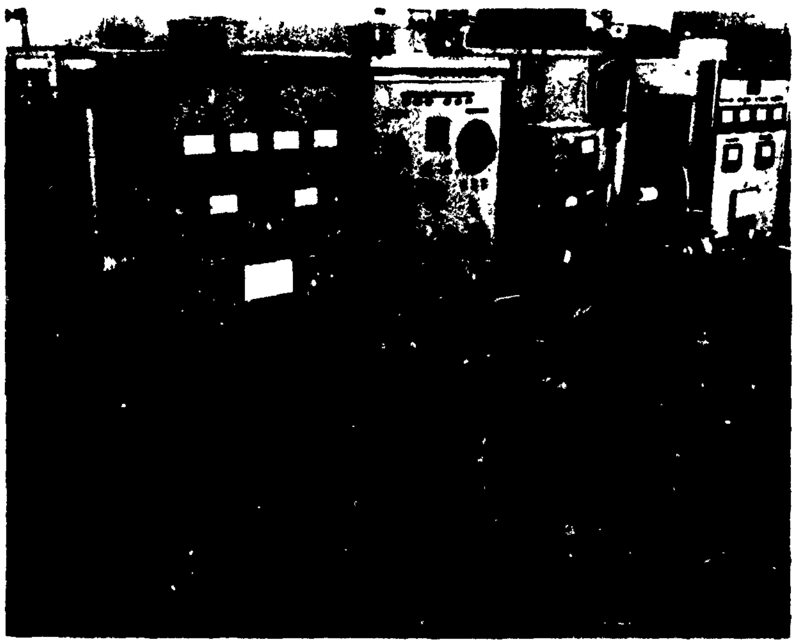


FIGURE 49 MODULATOR TEST POSITIONS

FIGURE 50 INCOMING PIECE PART CONTROL AND PILOT LINE SUPERVISION

FIGURE 51 HEATER AND CATHODE ASSEMBLY

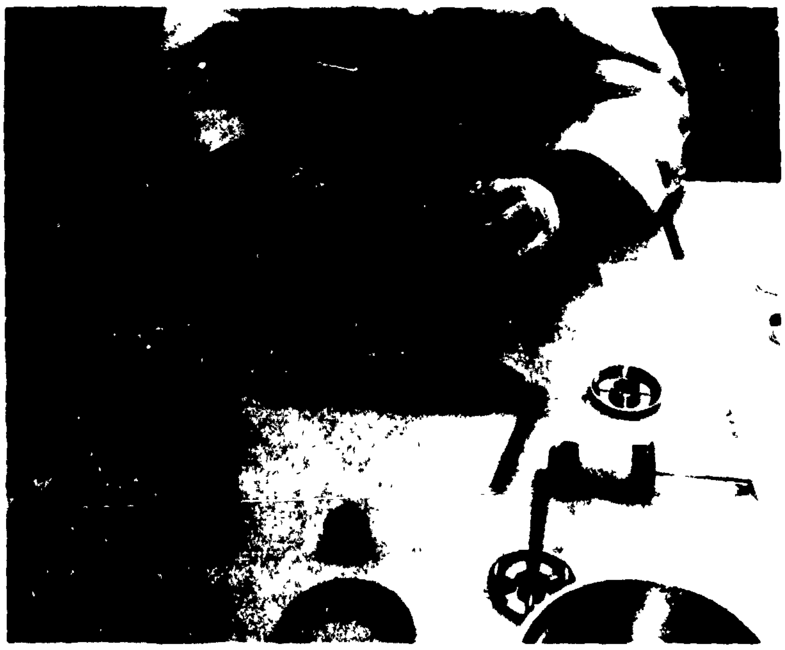


FIGURE 52 ANODE INSPECTION AND ASSEMBLY

FIGURE 53 CATHODE CENTERING INSPECTION PRIOR TO TUBE SEAL IN

FIGURE 54 FOUR-PORT VACUUM HEATING AND BRAZING UNIT

FIGURE 55 FOUR-POSITION RF BRAZING UNIT

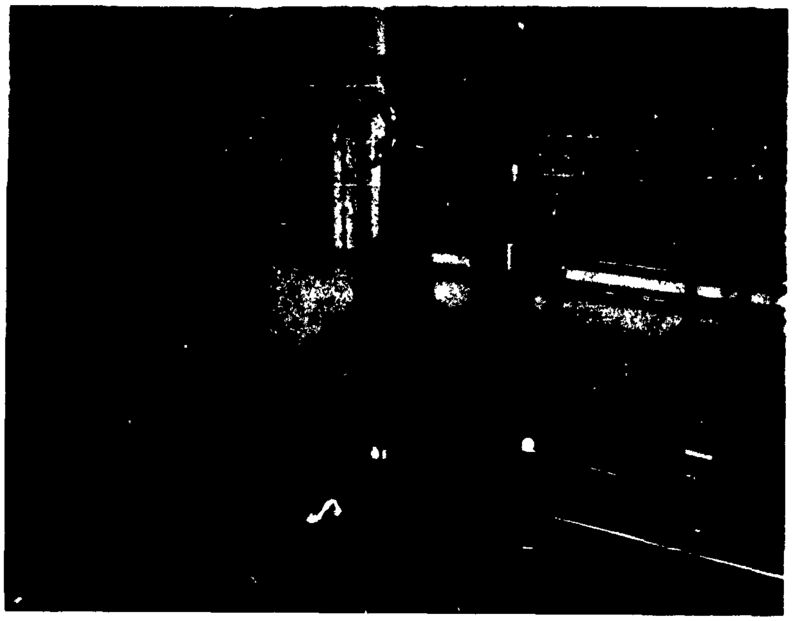


FIGURE 56   TYPICAL HELIARC FACILITY

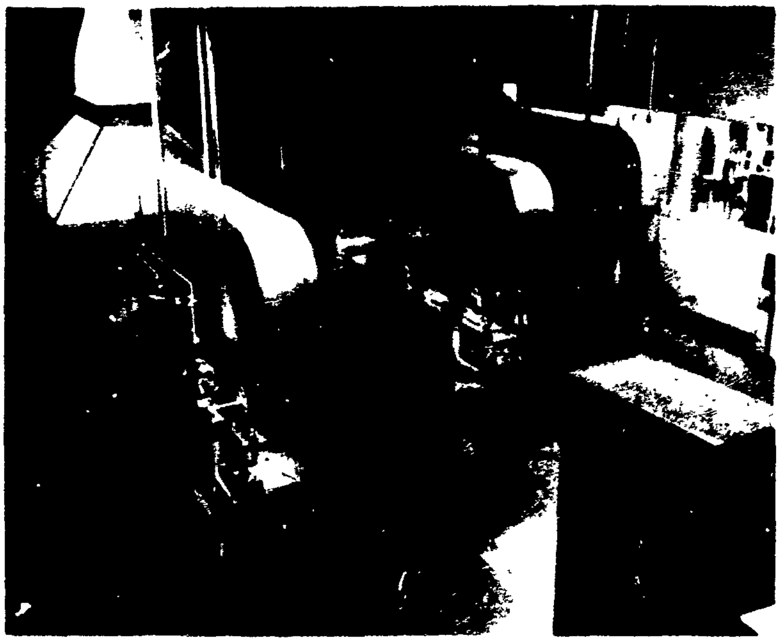


FIGURE 57   FURNACE BRAZING AREAS

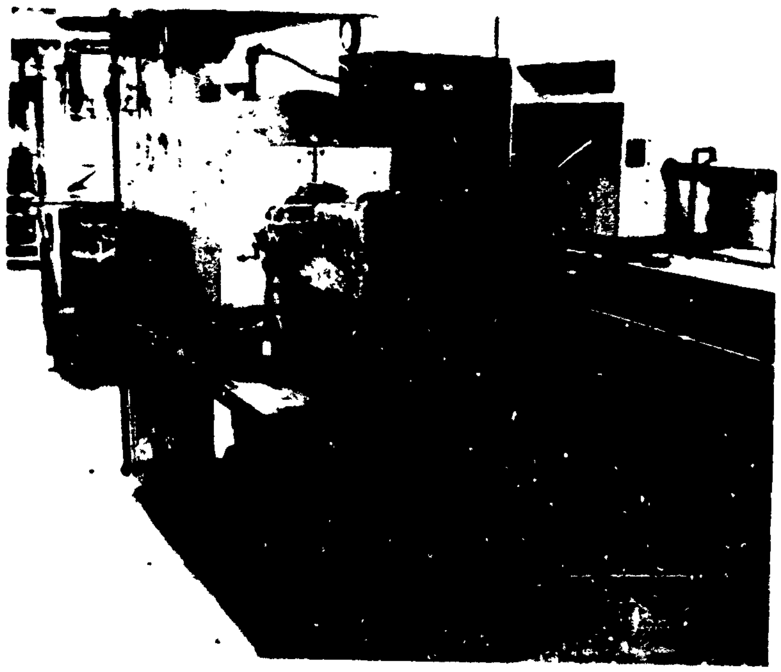


FIGURE 58 FURNACE VACUUM PROCESSING FACILITY

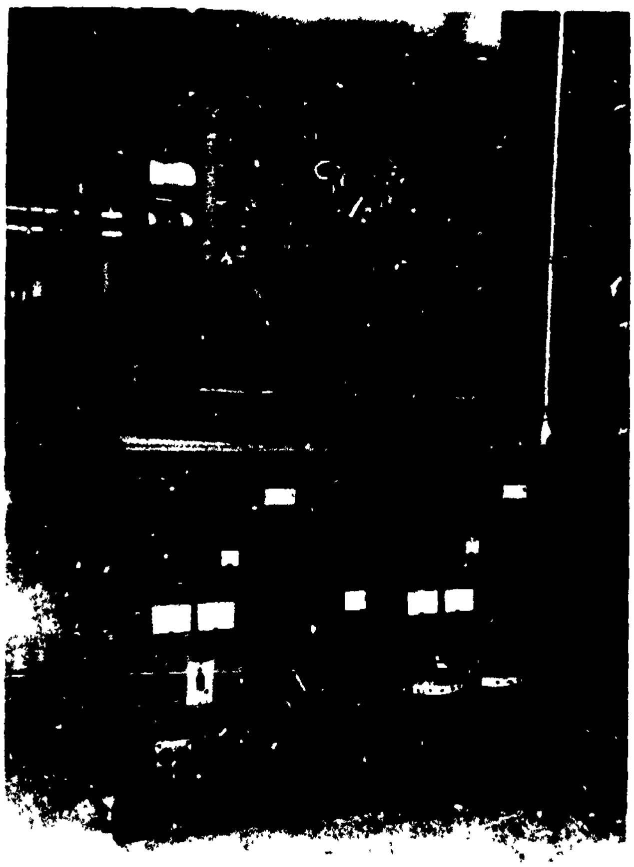


FIGURE 59 DU. L SYSTEM EXHAUST STATION

6.0 QUALITY CONTROL

The quality assurance program utilized throughout the construction of the SFD-328 inverted coaxial magnetron contained the following:

- Supplier quality program
- Vendor quality rating system
- Incoming material inspection
- Material review
- Material control
- In-process inspection procedures
- Purchasing
- Mechanical gage inspection and calibration program
- Mechanical gage calibration control
- Electrical test equipment calibration
- Quality control
- Final quality inspection

By adhering to these practices, S-F-D laboratories can produce items of high quality with reasonable yields.

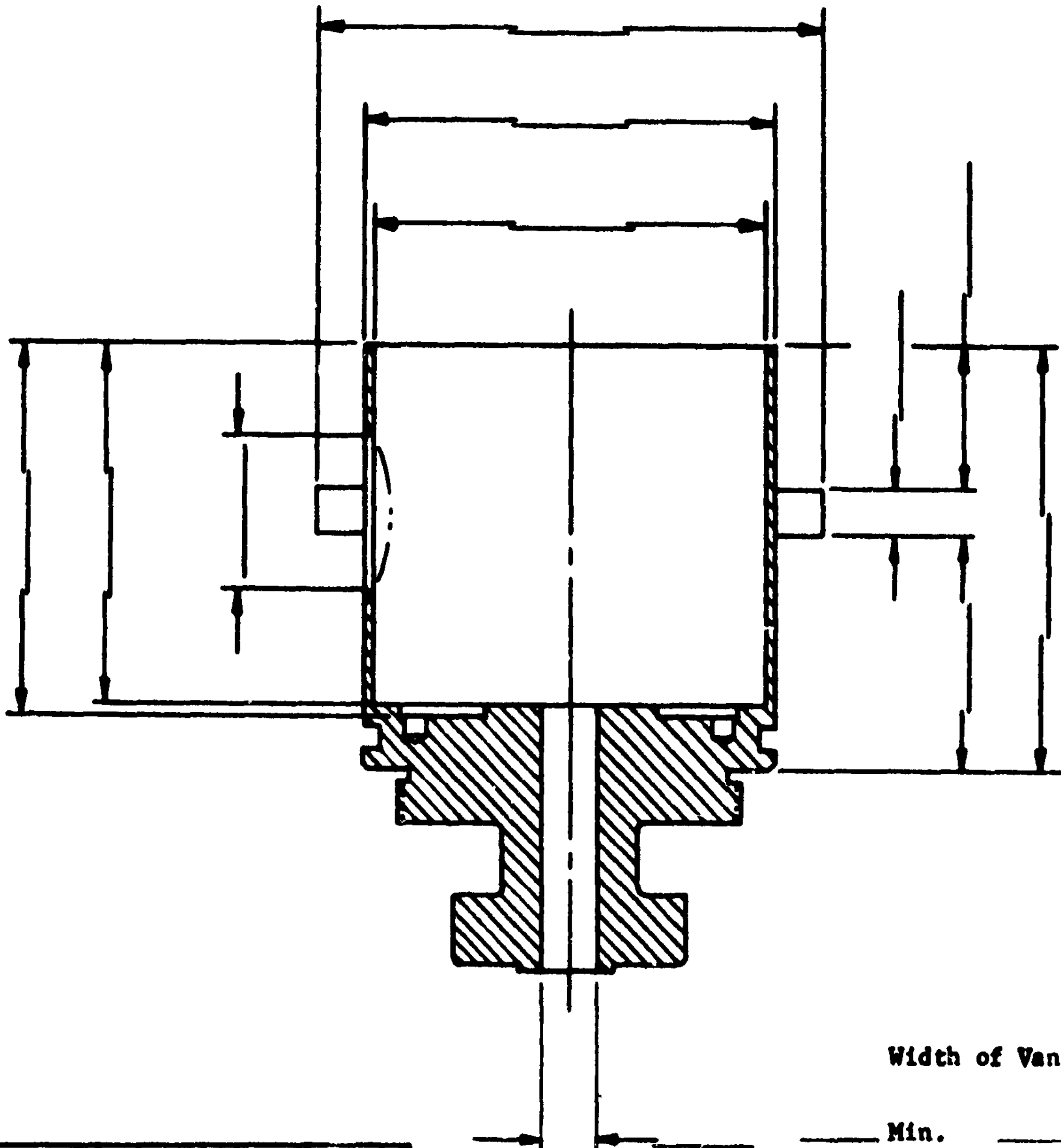
As part of the in-process inspection, the tubes are subjected to dimensional and alignment checks. The results of these tests are recorded on quality control follow sheets which are generated for each tube type. The SFD-328 follow sheets are included on the pages which follow.

These forms are used to survey critical assembly dimensions and are accumulated in "Tube Statistical Jackets" which contain a follow sheet for each major component of the magnetron. They are used to determine manufacturing deviations and to allow statistical distributions to be accrued.

The standard procedure instructions for the elements of the quality assurance program are included as Appendix II.

DWG. NO. ______________ TUBE NO. ______________ ANODE NO. ________

Dia. at 90°



DATE			
SMA			
DISC			
CAVITY			

Width of Vanes

_____ Min. _____ Max.

Vane Spacing

_____ Min. _____ Max.

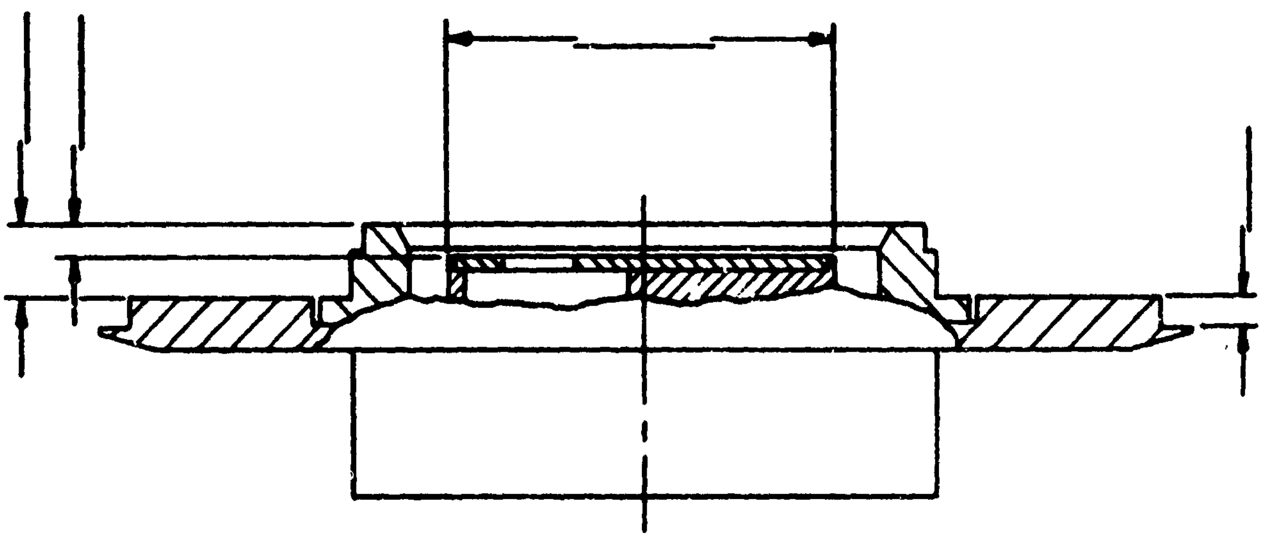
Slot Width

_____ Min. _____ Max.

M/S ratio ________ %

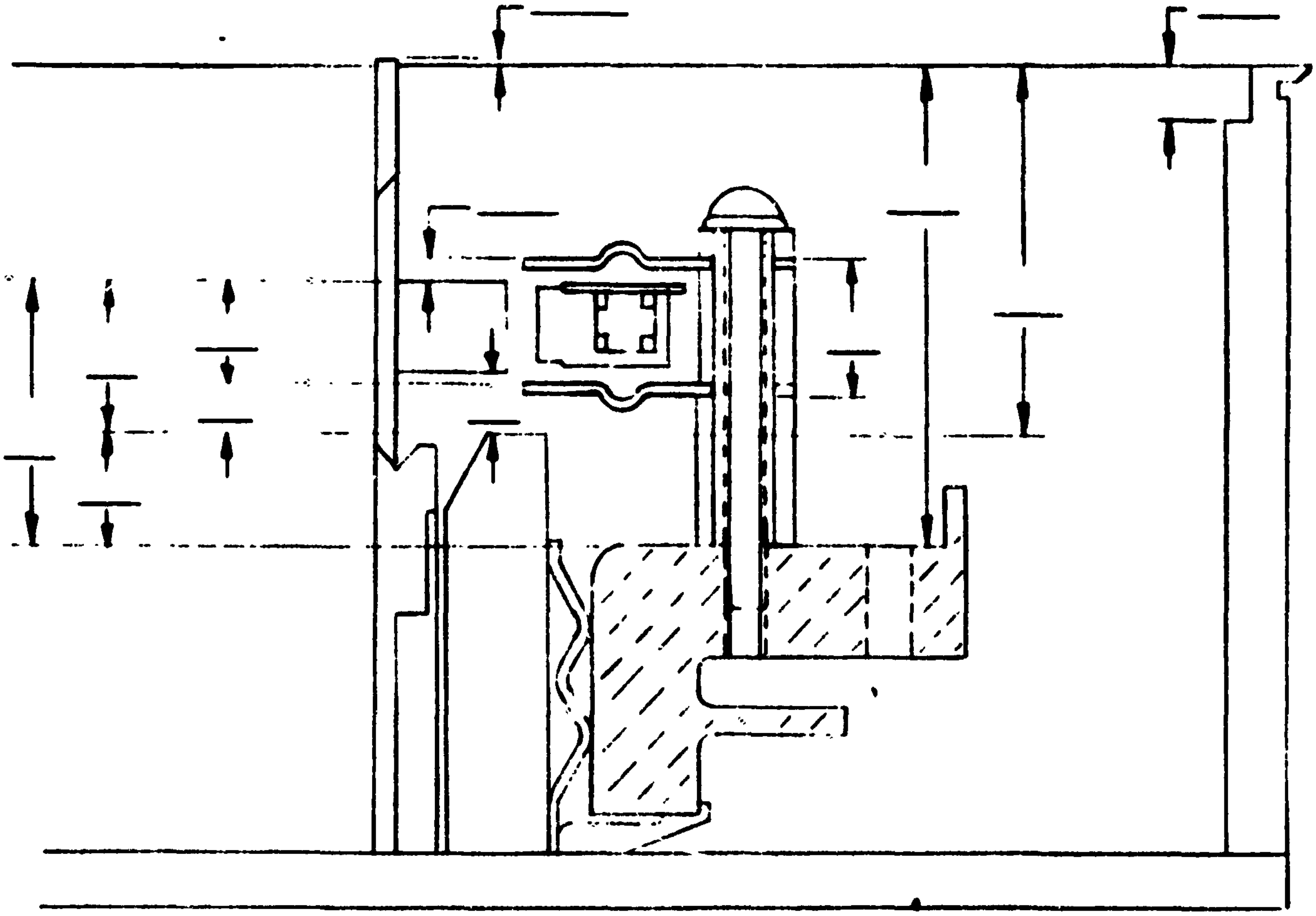
SFD-328 ANODE FOLLOW SHEET

ML-203



WINDOW NO. _______________

OUTPUT COVER FOLLOW SHEET



TUBE NO. ______________

BODY NO. ______________

ANODE NO. ______________

RES. ______________

CATHODE NO. ______________

HEATER RES. ______________

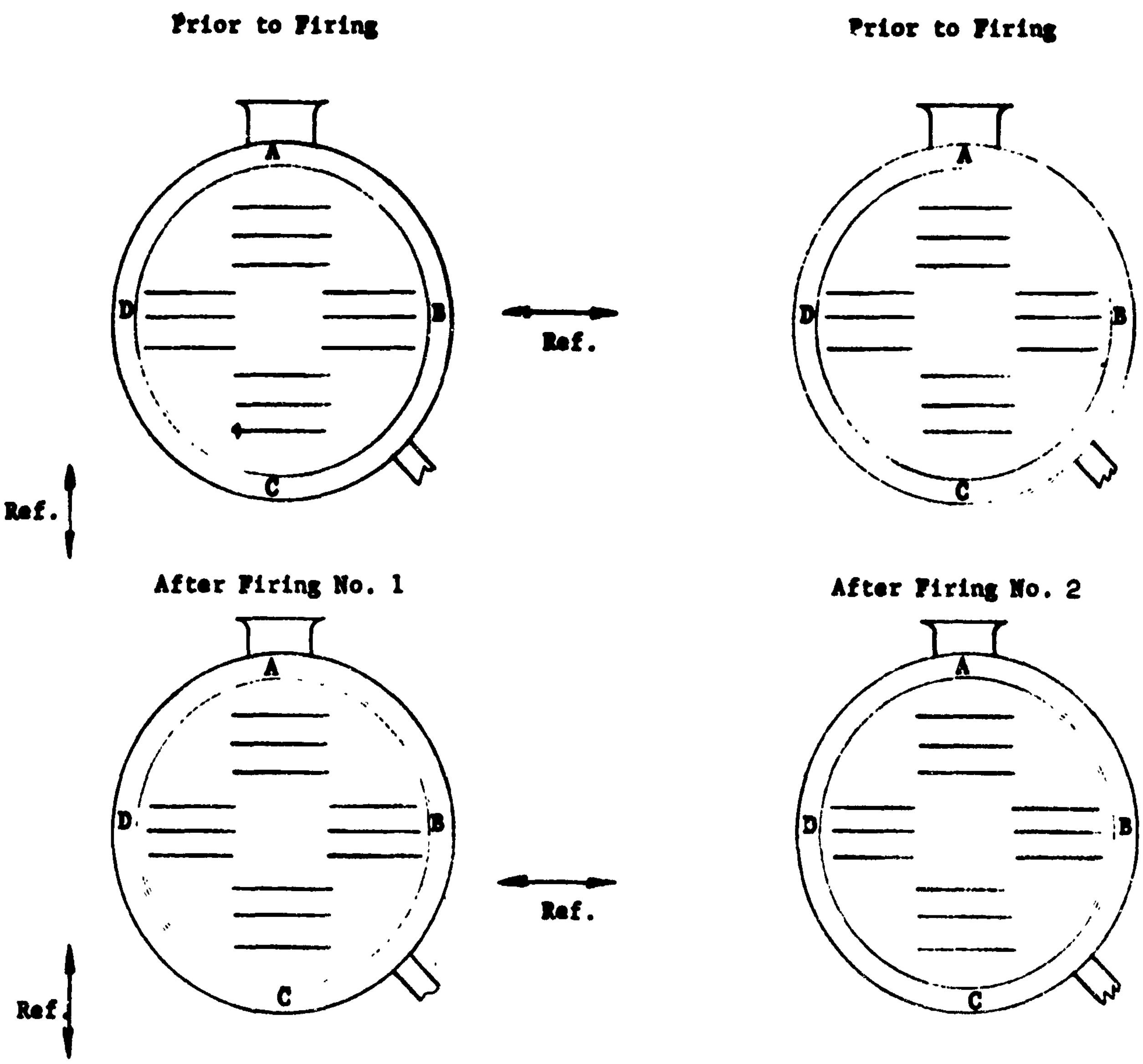
CATHODE I.D. ______________

END HAT I.D. ______________

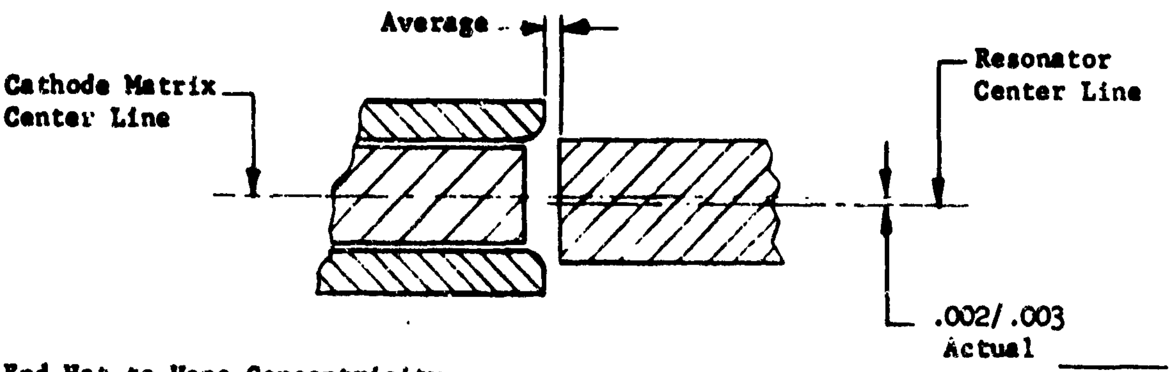
VANE DIA. ______________

ABS. TO VANE ______________

FINAL SEAL-IN FOLLOW SHEET



Depth from Ring to End Hat A ________ B ________ C ________ D ________



End Hat to Vane Concentricity

.002 TIR ACTUAL ____________

SFD-328 CATHODE CENTERING FOLLOW SHEET

Tube No. ____________________ Serial No. ____________________

SEAL-IN SHEET FOR SFD-328

Plant Order No.______________ Seal-In Date ______________

Electrical Engineer__________ Mechanical Engineer__________

Pole Piece Spacing __________ Vanes to Output Pole Clear_______

End Hat I.D.________________ Interaction Space______________

Cathode No.________________ Heater Wgt.__________________

Cathode I.D.________________ Absorber Gain in Wgt.___________

Attached to this seal-in sheet, there must be completed copies of the following:

ML-203 ML-205

ML-204 ML-206

Special Characteristics of this Tube:

ML-207

7.0 CONCLUSIONS

Since life testing of the final design tube, D14I, is still in progress, a major portion of the results of this program cannot be discussed fully. However, other factors, particularly those connected with reliability and reproducibility, can be discussed.

The electrical results, when compared to the revised specification sheet limits, are quite satisfactory and indicate a solid electrical design.

Anode thermal expansion exists on all tubes and, as previously discussed, limits the application of this device to one of constant duty factor, unless a major material study program is undertaken.

Still another mechanical problem, that of cathode movement, remains to be solved. The last tube built during the production phase had a new design cathode support, but it also showed evidence (voltage and efficiency fall-off) of cathode motion.

Of the four tubes built during the production phase, two failed during the early stages of testing. Tube G32I, built with the standard cathode support, failed during initial age in, due to a cracked cathode matrix assembly. Thus, no operating data are available for this tube.

A full power output curve was taken on tube D223I prior to failure, but failure occurred before a complete set of data could be taken. After opening, the tube was found to have a broken absorber, which had fallen into the anode vane structure.

The most practical solution to the mechanical problems is to reduce the size of the device, thereby minimizing thermal expansions, and allowing the use of conventional (such as used in Ka-band ICEM magnetrons) cathode support structures. Since frequency is inversely related to wavelength and circuit dimensions, a tube of higher frequency range such as Ku-band may be a more desirable application for a high power ICEM magnetron. A possible design for a Ku-band ICEM magnetron is included in Appendix III.

One of the most significant basic improvements of this program was the development of a direct rectangular waveguide output coupling section. This eliminated the need for large and costly circular-to-rectangular waveguide transitions.

The long life capability is being demonstrated in spite of the problem of cathode movement. It is expected that the 5000 hour life test will be concluded with no further major changes in tube performance.

REFERENCES

1. W. H. Kohl, MATERIALS AND TECHNIQUES FOR ELECTRON TUBES, Reinhold Publishing Corp. (1960), p 2

2. Bell Telephone Laboratories Staff, RADAR SYSTEM COMPONENTS, D. Van Nostrand Co. (1949), p 987

3. J. Feinstein and R. Collier, "A Magnetron Controlled by a Symmetrically Coupled TE_{011} Mode Cavity," LeVide, Vol 70, July-August 1957

4. E. D. Reed, "A Sweep Frequency Method of Q Measurement for Single-ended Resonators," Proc of Nat Elec Conf, Vol 7, 1951, pp 162-172

APPENDIX I

FINAL SPECIFICATION

ELECTRON TUBE, SFD-328 ICEM® MAGNETRON, PULSED

In addition to the specific references noted herein, this device shall conform with the applicable requirements of the latest issue of MIL-E-1.

DESCRIPTION: 8600-9600 MHz, tunable frequency, integral magnet, liquid cooled, 400 kw minimum peak power output, unipotential cathode.

ABSOLUTE RATINGS: (See note 1)

Independent:

Parameter	I_f(surge)	t_k	VSWR	T(body)	Tuner Drive Torque	Pressurization Input	Pressurization Output
Unit	amp	sec	----	°C	in-oz	psia	psia
Maximum	20	----	1.5:1	70	200	----	60
Minimum	----	300	----	----	----	15	(note 9)
				(note 4)	(note 20)	(note 14)	

Dependent:

Parameter	E_f	i_b	P_i	p_i	t_{pc}	rrv	du
Unit	v	amps	w	kw	µsec	kv/µsec	----
Maximum	25	70	1800	1800	3.0	100	0.001
Minimum	----	----	----	----	----	----	----
	(note 3)				(note 2)	(note 2)	

Mechanical:

Mounting position:	Any
Handling:	Note 17
Support:	Mounting flange
Cooling:	Liquid (note 18)(See Figure 1)
Outline:	See Figure 1
Coupling:	Mates with modified UG-52A/U
Magnet:	Note 19
Weight:	55 pounds nominal

MIL-E-1E METHOD	TEST	CONDITIONS	SYMBOL	LIMITS MIN	MAX	UNIT
	<u>General</u>					
----	Marking	See Figure 1	-	-	-	-
E.50.2	Holding period		-	168	-	hrs
----	Dimensions	See Figure 1	-	-	-	-
	<u>Qualification Inspection</u>					
----	Anode-cathode capacitance	--	c	60	85	pf
1136	Container drop	Not required	-	-	-	-
----	Shock	g = 50; t = 4 msec (see notes 6, 7)	-	-	-	-
1031-6	Variable frequency vibration (non-operating)	Note 7	-	-	-	-
	<u>Quality Conformance Inspection Part 1</u>					
4003	Pressurization	45 psia (minimum) Output assembly (note 8)				
1301	Heater current	E_f = 23 v t_k = 300 sec (min)	I_f	8.0	10.0	amp
----	Tuner drive torque	T(ambient) = $20 \pm 10^\circ C$	Torque	-	15	in-oz
	<u>Oscillation (1)</u>	Note 18				
	Coupling	VSWR = 1.1:1 max except as noted Note 9				
----	Tunable frequency	T(body) = $50 \pm 10^\circ C$ Note 5	F	-	-	MHz
		Upper limit		F_5	-	
		Lower limit		-	F_1	

MIL-E-1E METHOD	TEST	CONDITIONS	SYMBOL	LIMITS MIN	MAX	UNIT
4303	Heater-cathode warm-up time	E_f = 23 v t_k = 300 sec max E_f = 17 v for test Note 3	-	-	-	-
4304	Pulse characteristics	t_{pc} = 2.5±0.25 μsec du = 0.001 rrv = 100 kv/μsec min Notes 2, 10	-	-	-	-
4305	Average anode current	I_b = 60 ma dc	-	-	-	-
4306	Pulse voltage	$F = F_1$ to F_5 Note 5	e_{py}	23	27	kv
4307	Power output	$F = F_1$ to F_5 Notes 5, 11	P_o	400	-	w
4308	RF bandwidth	$F = F_1,F_3,F_5$ Notes 5, 12	BW	-	$2.4/t_{pc}$	MHz
4308	Spectrum minor lobes	$F = F_1,F_3,F_5$ Notes 5, 12	SL	8	-	db
4315	Stability	$F = F_1,F_3,F_5$ Notes 5, 12, 13	MP	-	0.5	%
	Quality Conformance <u>Inspection Part 2</u>					
4310	Pulling factor	$F = F_1,F_5$ Note 5	ΔF	-	6.0	MHz
4311	Pushing factor	$F = F_1,F_5$ Osc. (1); i_b = 58-62 amps Notes 5, 15	ΔF/ΔI	-	0.1	MHz/a
	Quality Conformance <u>Inspection Part 3</u>					
	Intermittent life test operation	Group D Note 16	life	-	10,000	hrs
	Intermittent life test end points	Osc (1)				

MIL-E-1E METHOD	TEST	CONDITIONS	SYMBOL	LIMITS MIN	MAX	UNIT
4307	Power output	$F = F_1, F_3, F_5$ Notes 5, 11	P_o	320	-	w
4308	RF bandwidth	$F = F_1, F_3, F_5$ Notes 5, 12	BW	-	$2.5/t_{pc}$	MHz
4308	Spectrum minor lobes	$F = F_1, F_3, F_5$ Notes 5, 12	SL	6	-	db
4315	Stability	$F = F_1, F_3, F_5$ Notes 5, 12, 13	MP	-	1.0	%

NOTES:

1. The requirements of paragraph 6.5 of MIL-E-1 shall apply. For the assistance of designers of electronic equipment, the ratings have been divided into two groups as follows:
   a. Independent - ratings which may be obtained simultaneously
   b. Dependent - ratings which are interrelated and may not necessarily be obtained simultaneously.

2. The characteristics of the applied pulse must be those which result in proper starting and oscillation. The rate of rise of voltage pulse, the percentage of pulse voltage ripple, and the rate of fall of voltage pulse are among the more important considerations.

3. Prior to the application of high voltage, the cathode shall be heated to the required initial operating temperature. This shall be done by applying 23.0 volts ± 5 percent for 300 seconds minimum. Heater voltage is to be reduced during operation whenever the average input power exceeds 200 watts. Above 200 watts of average input power, the heater voltage shall be reduced in linear relationship with the average input power so that with 1600 watts of average input power, the heater voltage shall be 17 volts ± 5 percent.

4. The temperature is to be measured at the point indicated on Figure 1.

5. The frequency designations shall be as follows:

Code	Frequency - MHz
F_1	8600
F_2	8850
F_3	9100
F_4	9350
F_5	9600

6. The magnetron shall be mounted on a test plate and subjected to three shocks in each of three mutually perpendicular planes.

7. After the specified test, no physical change affecting performance shall result and the sample shall meet the requirements of Oscillation (1).

8. The specified pressure shall be applied to the tube output. There shall be no leak as indicated by metered pressure fall off or by bubbles if the test is performed with the tube immersed in water. The time of the test shall be 1 minute minimum.

9. The gas used for pressurization shall provide insulating properties consistent with the power levels required. The minimum pressure is, therefore, dependent upon the type of insulating gas used.

10. For definitions regarding voltage and current pulse characteristics, refer to Figures 4304-1 and 4304-2 of Method 4304 of MIL-E-1.

11. The power output shall be the minimum specified over the frequency range, F_1 to F_5.

12. The radio frequency (RF) bandwidth, minor lobes, and stability shall be within the specified limits when a VSWR of 1.5:1 minimum is introduced in the load, the phase being adjusted for worst spectrum or worst stability.

13. Stability shall be measured in terms of the number of output pulses missing, expressed as a percentage of the number of input pulses applied during the period of observation. The missing pulses (MP) due to any cause are considered to be missing if the RF energy is less than 70% of the normal energy level. The missing pulse count shall be performed during any 3 minutes of a 6 minute test interval.

14. The magnetron shall be capable of normal operation without electrical breakdown with the input bushing at normal atmospheric conditions.

15. Peak current through the magnetron shall alternately be the limits as specified under the test conditions. The test shall be performed to exclude the effects of thermal drift and frequency instability not due to pushing.

16. The life test shall be conducted in accordance with the following schedule:

Condition	I_b (ma dc)	E_f (v)	Duration
Standby	0	23.0	300 sec (max)
Oscillation (1)	60	17.0	*
Off	0	0	1 hour

*The duration of the oscillation time shall be 6 hours or greater; however, no less than 8 complete cycles shall be accumulated in any 168 hour calendar period. Such a schedule permits attended switching and routine maintenance. The accumulation of life hours shall apply only to radiate ON time. The tube shall be tuned throughout the life test to insure approximately equal radiate time at each of the test frequencies (F_1, F_2, F_3, F_4, and F_5).

17. Care shall be exercised in the storage, installation, and handling of the tube to avoid imparting vibration or shock in excess of the values for which it is designed to withstand.

18. Adequate cooling of the tube is provided when 1.0 gal/min of water is delivered through the cooling manifold. Use of liquid coolants different from water is permitted provided the flow rate is adjusted to provide equivalent cooling.

19. In handling and mounting the magnetron, care shall be taken to prevent demagnetization. Ferromagnetic materials shall not at any time be permitted to come closer than 8 inches from the magnet. Energized magnets shall not at any time be permitted to come closer than 12 inches from the tube magnet.

20. The tuner drive shall be capable of supplying a minimum of 15 inch-ounces of torque to the magnetron tuning shaft and shall never supply more than 200 inch-ounces of torque including inertial effects.

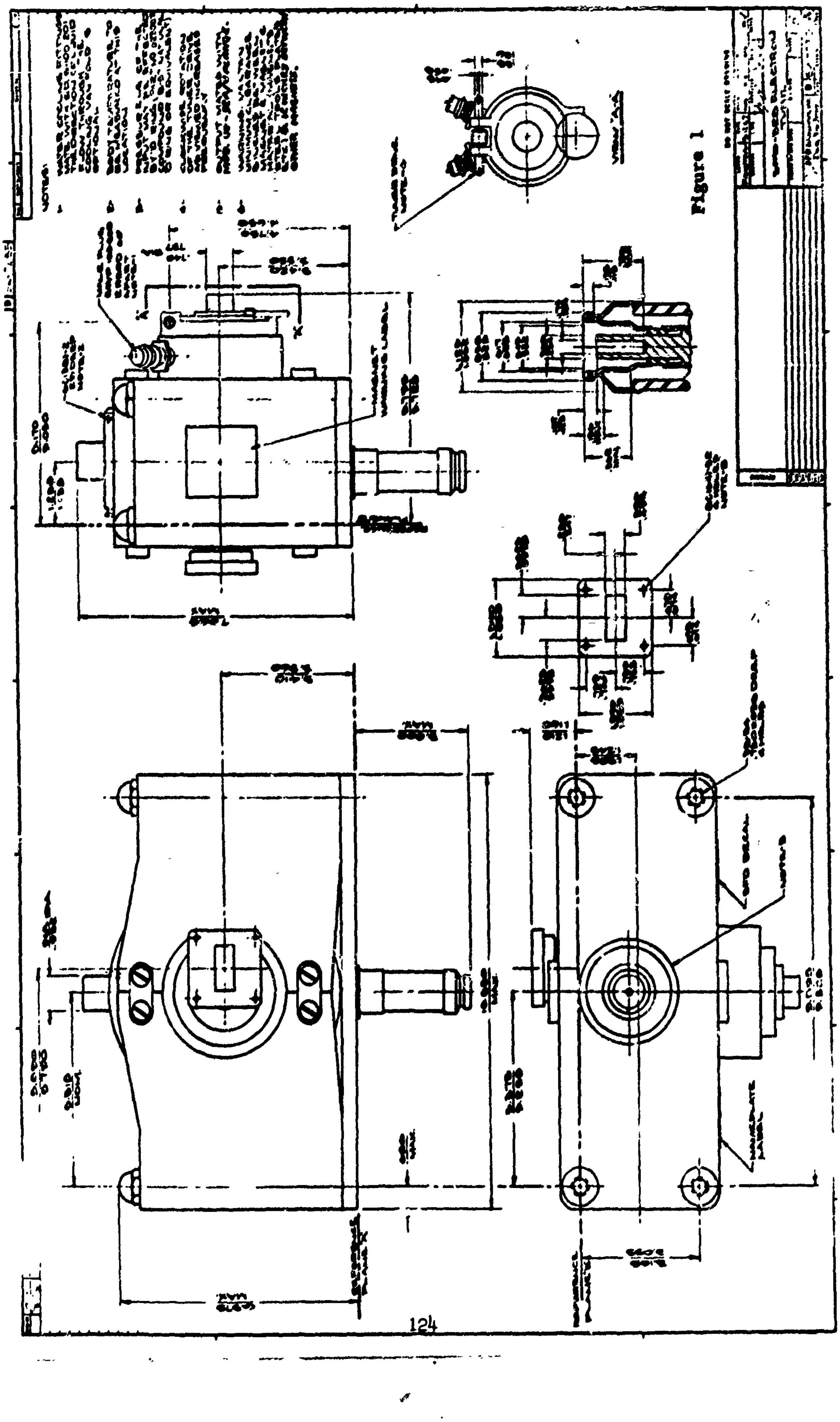


Figure 1

APPENDIX II

STANDARD PROCEDURE INSTRUCTIONS

STANDARD PROCEDURE INSTRUCTIONS

Title: SUPPLIER QUALITY PROGRAM

1. Purpose

S-F-D Laboratories conducts surveys of the facilities and Quality Control Systems of its suppliers and prospective suppliers prior to their qualification as material, equipment, or service suppliers, for the purpose of ascertaining the level of Quality Control prevalent at the supplier's facility and the general capabilities of the company.

2. Conditions Warranting a Supplier Survey

2.1 A prospective supplier requires qualifications prior to his acceptance.

2.2 A present supplier whose work is of poor quality must be re-evaluated to assure his continued acceptance as a supplier.

2.3 The relocation of a supplier's facilities.

2.4 Gross changes occur in the supplier's management or in his method of operation.

2.5 A change in the nature of parts supplied, i.e., a many-fold increase in the amount of supplied material, the utilization of supplier facilities unused previously, etc.

3. Supplier Survey as an Auditing Medium

Supplier Surveys act as an auditing medium for suppliers with recurrent poor quality performance with regard to their continued acceptance. The auditing of this class of supplier normally has precedence over the previously mentioned conditions and is done in the following order of priority:

3.1 Suppliers whose merchandise is, for quality reasons, in short supply, and which can or has caused production delay or stoppage.

3.2 Suppliers with declining quality performance, but whose parts are not currently in short supply.

3.3 Suppliers whose parts meet the minimum quality standards, but on which there is no recent process or facilities information.

Title: SUPPLIER QUALITY PROGRAM

4. Preparations Prior to Survey of Supplier's Facility

4.1 The Purchasing Department at S-F-D is the central coordinating point in all matters relating to a supplier, hence any contemplated supplier surveys are coordinated with Purchasing so that appropriate arrangements can be made with the supplier.

4.2 Prior to the actual survey, the assigned Quality Assurance or technical personnel are required to brief themselves on all details concerning the supplier and his products. Some of the documents used for such a briefing include the following:

a. Applicable product specifications.

b. Applicable purchasing requirements, including a copy of the purchase orders.

c. Applicable quality and reliability requirements.

d. A compilation of characteristics requiring special attention.

e. Recent supplier quality rating data.

f. Other survey reports or data relating to the supplier.

4.3 In those cases when a survey is to be conducted by other than Quality Assurance personnel, the survey personnel will confer with the Quality Assurance Manager, to discuss ways of conducting the survey, the preparation of paperwork, and the reporting of findings.

5. Supplier Quality Survey Forms

The Supplier Quality and Facility Survey (SFD Form No. 74), is used as the basic tool in evaluating the present and future production and quality capabilities of all suppliers. This form consists basically of two parts:

5.1 The first part of SFD Form No. 74 is concerned with general production and quality information, such as numbers and types of personnel, equipment, processes, etc.

5.2 The second part of SFD Form No. 74 is concerned with detailed quality control functions. This section is in the form of an evaluation sheet which is ultimately used to rate the quality aspects of the supplier. The functions scrutinized in this section include among others: all phases of material control, product control, process control, material review, etc.

6. Supplier Quality Rating System

6.1 The evaluation portion of the Supplier Quality Survey has a rating section by which every applicable item on the form is given a rating, from "0" for unacceptable to "3" for above average. An arithmetic average is computed from these individual ratings which has a value of from "0" to "100". This average is the Supplier Quality Rating.

6.2 Results of the Supplier Quality Rating.

6.2.1 All suppliers are placed in quality categories as a result of the survey rating. These categories are:

a. Approved.

b. Conditionally approved.

c. Disapproved.

6.2.2 All surveys are reviewed by the Quality Assurance Manager prior to release to Purchasing and rating release to the supplier.

6.2.3 Upon the completion of the survey review, S-F-D Laboratories notifies the supplier as to his rating. If the rating is "conditionally approved", the supplier is notified of those areas which are weak and suggestions are given for their improvement. An abbreviated survey is made after three to six weeks in order to ascertain the compliance to the advised changes to be made. If after that time, or any other preset time the quality level has not appreciably improved, the supplier's rating is changed to "disapproved" and any applicable supplier contracts are subject to termination.

6.2.4 Any supplier with a rating of "disapproved" can request a re-evaluation at such time as its quality level is capable of passing the Supplier Quality Survey.

STANDARD PROCEDURE INSTRUCTIONS

Title: VENDOR QUALITY RATING SYSTEM

GENERAL DESCRIPTION

1. Each Vendor doing business with S-F-D Laboratories is assigned a Vendor's Quality Rating for each rating period in which he supplies the company with materials. The rating assigned reflects the quality and quantity of shipments received during the period.

2. The Rating Period is to be one of three calendar months, starting on the first of the month.

3. The VQR is a product of three separate factors:

   3.1 The average percent of lot samples found acceptable non-defective, $\overline{PSA}$

   3.2 The fraction of lots received which were acceptable, based on AQL requirements of MIL-STD-105. $\overline{FLA}$

   3.3 A weighting factor for the total number of lots received from the vendor during the rating period $\sqrt{\frac{L}{L+1}}$

4. The VQR equation form is as follows:

$$VQR = \overline{PSA} \times \overline{FLA} \times \sqrt{\frac{L}{L+1}}$$

A more explicit explanation of the mechanics of computing the VQR will be found on the following pages, along with a sample computation of the rating.

5. Determination of the Vendor Quality Rating

   5.1 The following terms will be used to compute the VQR, Vendor's Quality Rating, for each rating period.

   5.1.1 n = Total sample size for any Lot.

   5.1.2 d = Number of defects in any Lot sample

   5.1.3 L = Number of Lots received during any rating period.

   5.1.4 A = Number of Lots accepted during any rating period.

ML-69

Title: VENDOR QUALITY RATING SYSTEM

5.1.5 PSD = Percent of sample defective for any Lot received.

5.1.6 Σ PSD = Sum of all PSD's for any rating period.

5.1.7 $\overline{PSD}$ = Average percent of sample defective for any rating period.

5.1.8 $\overline{PSA}$ = Average percent of sample acceptable for any rating period.

5.1.9 FLA = Fraction of all lots accepted during any rating period.

5.1.10 VQR = Vendors's Quality Rating.

a) A VQR of 0-64 is considered unacceptable.

b) A VQR of 65-100 is considered acceptable.

5.2 Computations

5.2.1 $PSD = (d/n) \times 100$

5.2.2 $PSD = PSD_1 + PSD_2 + \ldots + PSD_L$

5.2.3 $\overline{PSD} = \Sigma PSD/L$

5.2.4 $PSA = 100 - \overline{PSD}$

5.2.5 $FLA = A/L$

5.2.6 $VQR = \overline{(PSA)} \times \overline{FLA} \times \sqrt{\frac{L}{L+1}}$

Title: VENDOR QUALITY RATING SYSTEM

5.3 **Example:**

Lot	Lot Size	(n) Sample Size	(d) Defects	Acc.	Rej.
1	1000	110	2	✓	
2	2000	200	8		✓
3	650	75	0	✓	
4	1000	110	0	✓	
L=4				A=3	

$PSD_1 = d/n = 2/110 = 1.82\%$

$PSD_2 = d/n = 8/200 = 4.00\%$

$PSD_3 = d/n = 0/75 = 0\%$

$PSD_4 = d/n = 0/110 = 0\%$

$PSD = 5.82\%$

$\overline{PSD} = \frac{\sum PSD}{L} = \frac{5.82}{4} = 1.46\%$

* $\overline{PSA} = 100 - \overline{PSD} = 100 - 1.46 = \underline{98.54\%}$

* $FLA = A/L = 3/4 = \underline{.75}$

* $\sqrt{\frac{L}{L+1}}$ = From Table; $L = 4, \sqrt{\frac{L}{L+1}} = \underline{.89}$

$VQR = (\overline{PSA}) \times (FLA) \times \sqrt{\frac{L}{L+L}} = (98.5) \times (.75) \times (.89) = \underline{65.7\%}$

$\underline{VQR}$ = 65.7% - Vendor Acceptable

Title: VENDOR QUALITY RATING SYSTEM

TABLE FOR COMPUTION OF $\sqrt{\frac{L}{L+1}}$

L					$\sqrt{\frac{L}{L+1}}$
0	--	--	--	--	0.00
1	--	--	--	--	.71
2	--	--	--	--	.82
3	--	--	--	--	.86
4	--	--	--	--	.89
5	--	--	--	--	.91
6	--	--	--	--	.93
7-8	--	--	--	--	.94
9-10	--	--	--	--	.95
11-14	--	--	--	--	.96
15-21	--	--	--	--	.97
22-38	--	--	--	--	.98
39-198	--	--	--	--	.99
199 & Up	--	--	--	--	1.00

STANDARD PROCEDURE INSTRUCTIONS

Title: INCOMING MATERIAL INSPECTION

1. General:

All purchased materials used in the fabrication of finished products must be subjected to Incoming Material Inspection, and accepted under one of the procedures described below, before use is permitted. In addition, bulk chemicals used in the fabrication process must also be approved. For this purpose, S-F-D laboratories, inc., provides the following facilities:

1.1 Material Inspection group which performs all mechanical, dimensional, and functional tests.

1.2 A Chemical and Metallurgical Laboratory which performs chemical analyses on parts and raw materials.

1.3 The services of outside consulting laboratories for special tests, spectrographic analyses, etc.

2. First Piece Approvals:

All new parts and/or materials must be subjected to a detailed First Piece Inspection, the results of which are recorded on a "Sample Report" (SFD Form No. 75). This must then be reviewed and approved by the Product Engineering Manager before the authorization to proceed with production is given.

The results of the first piece inspection are then kept on permanent file in the Material Inspection Department and are compared with the results of subsequent production shipments.

3. Production Materials Inspection Procedures:

3.1 A random sample is selected from each lot of incoming parts. The sample size depends on the quantity of incoming parts as outlined in MIL-STD-105. Single sampling is employed.

3.2 The sample lots are inspected for dimensional and quality characteristics using a 0% AQL for critical defects, a 1% AQL for major defects, a 2.5% AQL for minor defects, and a 6.5% AQL for control defects, unless otherwise specified.

3.3 Disposition of Inspected Lots:

Results of inspection shall be recorded with review by the Chief of MID for disposition.

3.3.1 Lots which pass inspection shall be passed through to Material Control.

3.3.2 Lots which fail inspection are subject to being returned to the appropriate vendor.

Title: INCOMING MATERIAL INSPECTION

3.3.2.1 Lots which are out of specification limits due to a major defect shall be returned to the vendor.

3.3.2.2 Lots which are out of specification limits on a minor or control defect shall be submitted to the Material Review Board for disposition.

3.4 Materials which require a certificate of conformance, compliance, or analysis are also checked for evidence of the certificate.

3.5 An individual Lot By Lot Record of Sampling Inspection (SFD Form No. 78) is recorded by the Material Inspector for each applicable purchased product type, consisting of date, lot size, and defects found. A record of chemical analyses is provided on SFD Form No. 84 (Incoming Raw Material Inspection) or on SFD Form No. 51 (Chemical Spot Testing of Materials) which is filled out by the Chemical and Metallurgical Laboratory. Both forms are filed permanently in the supplier's folder.

3.6 An Incoming Material Inspection Report (SFD Form No. 76) which compares the product conformance with the specification is also retained on all incoming material.

3.7 All material which is accepted is placed in the Material Control Area. Material can only be withdrawn from stock by means of Material Requisition (SFD Form No. 67)

3.8 Defective material is reported on a Weekly Defective Material Report (SFD Form No. 79).

3.9 Materials that do not conform to specification are submitted to the Material Inspection Review Board consisting of the Quality Assurance Manager, Manufacturing Manager, and Product Engineering Manager.

After a thorough investigation is conducted, the Review Board will make its decision as to the disposition of the material. This disposition may be that the material should be 100% inspected, reworked, returned to the vendor, scrapped, etc.

3.10 Materials found to be discrepant in any way are reported to the Purchasing Department which notifies the supplier by means of a Vendor Corrective Action Request (SFD Form No. 80) of the existing defects.

4. Incoming Inspection Records:

The following records will be maintained and distributed as outline in this procedure.

Title: INCOMING MATERIAL INSPECTION

4.1 Print Folder.

4.1.1 Print folders are filed numerically by part number.

4.1.2 Items to be filed in folder

a. Correspondence - not relating to specific supplier.

b. Print changes and deviations

4.2 Supplier Folder.

4.2.1

4.2.2 Suppliers to be filed alphabetically.

4.2.3 Items to be filed in folder by date.

a. Sample Report - First Piece Approvals.

b. Correspondence and deviations relating to the supplier.

c. Incoming Material Inspection Reports (SFD form No. 76).

d. Vendor Lot By Lot Inspection Record (SFD Form No. 78).

4.3 Distribution of Forms and Records.

4.3.1 Vendor Lot By Lot Inspection Record (SFD Form No. 78).

a. Incoming Material Inspection - 1 copy

b. Purchasing - 2 copies

1) Part No. File - 1 copy

2) Supplier File - 1 copy

4.3.3 Weekly Defective Material Report

(SFD From No. 79)

a. Quality Assurance Manager - 1 copy

b. Purchasing - 2 copies

c. Incoming Material Inspection General File - 1 copy

d. Product Managers - 1 copy

e. Manufacturing Manager - 1 copy

f. Assistant General Manager - 1 copy

Title: INCOMING MATERIAL INSPECTION

4.3.4 Incoming Material Inspection Report (SFD Form No. 76)

a. Incoming Material Inspection Supplier Folder - 1 copy (Quality Assurance copy)

b. With Material - 1 copy (Parts Traveler copy)

c. Purchasing - 1 copy

d. Material Control - 1 copy

e. Vendor - Vendor copy (if material is rejected and is to be returned)

f. Product Manager - 1 copy (Parts Traveler Copy when material reaches destination)

g. Accounting - Vendor copy (if material is accepted).

4.3.5 Request for Vendor Corrective Action (SFD Form No. 80)

a. Vendor - 2 copies

1) Vendor Reply copy (To be returned to Quality Assurance Manager, S-F-D)

2) Vendor File copy

b. Purchasing - 1 copy

c. Incoming Material Inspection - 1 copy

4.3.6 Sample Report - First Piece Approvals (SFD Form No. 75)

a. Incoming Material Inspection Supplier Folder - 1 copy

b. Product Manager - 1 copy

c. Purchasing - 1 copy

d. Quality Assurance Manager - 1 copy

STANDARD PROCEDURE INSTRUCTIONS

Title: MATERIAL REVIEW

1. Purpose

1.1 This SPI establishes a procedure in accordance with the policy of relying on multiple judgement whenever practical for the purpose of review, control, and disposition of nonconforming material.

1.2 The primary purpose of the procedure outlined herein is to eliminate the causes of recurring discrepancies and to prevent the occurrence of similar discrepancies. This procedure will apply to material which, due to improper or faulty processing, requirements specified in the contract, specification, drawing, purchase order, or other applicable product description. This procedure does not include material rendered obsolete because of design changes, nor material which has been altered or substituted as a result of planned engineering changes which are subject to formal approval by the Manufacturing Manager, Assistant General Manager, or their designated representatives.

2. Definitions

2.1 "Nonconforming Supplies"

Any material, part, or product in which one or more characteristics do not conform to the requirements specified in the contract, specification, drawing, purchase order, or other applicable product description.

2.2 "Material Review Board"

A formal board of review established for the purpose of reviewing, assuring corrective action, and determining the disposition ("rework," "use as is," "scrap," etc.) of non-conforming supplies which are referred to it.

3. The Material Review Board

3.1 Members of the Material Review Board

3.1.1 A qualified representative of the Quality Assurance Department.

3.1.1.1 Quality Assurance Manager

3.1.1.2 This member serves as Chairman of the MRB

3.1.1.3 Additional Responsibilities

a. Review of discrepant material prior to requesting Board actions.

b. Calling the appropriate personnel together for an MRB meeting.

c. Recording all MRB action

d. Follow up of Corrective Action Requests and Vendor Off-Specification Permits. This function is audited by the Quality Assurance Representative.

Title: MATERIAL REVIEW

3.1.2 The Product Engineering Manager whose product is affected by the MRB decision.

3.1.3 The manufacturing Manager of S-F-D laboratories.

3.1.4 A Technical Specialist.

a. e.g.: Glass technologist, chemist, metallurgist, etc.

b. Acting in an advisory or consultant capacity only.

c. Called to Board Meeting upon request of other MRB members.

3.2 The Material Review Board has the authority and responsibility to act in any situation pertaining to incoming and in-process material when the material in question has been rejected by Incoming Material or In-Process Inspection, and it is the opinion of the Quality Assurance Manager that the final disposition of the material shall be decided by the MRB.

3.3 Disposition of Nonconforming Material by the Material Review Board

The Material Review Board is authorized to determine the disposition of nonconforming material. It is acknowledged by the Board that discrepancies can exist with regard to material specifications and drawings and an acceptable standard of workmanship. There are several courses of action available to the Board with which it can cope with the discrepant material, depending on individual circumstances:

3.3.1 Return material to vendor.

3.3.2 Scrap material in plant.

3.3.2.1 Vendor's expense.

3.3.2.2 S-F-D laboratories expense

3.3.3 Rework material and reinspect for acceptability.

3.3.3.1 Vendor's expense

3.3.2.2 S-F-D laboratories expense

3.3.4 If the material is out of specification but useable "as is," the shipment may be accepted.

3.3.4.1 When the discrepancies in question in no way affect the functioning, assembly, maintenance, life or appearance of the material, and are not departures from established standards, a request may be made to change the existing specifications, after which the material would be subject to reinspection for compliance with the new specification.

Title: MATERIAL REVIEW

3.3.4.2 In those cases where a change in existing specifications is not warranted, and functioning, maintenance, or life of the material is not impaired, the material may be accepted, advising the vendor by means of a Vendor Corrective Action Request (SFD Form No. 80) that future shipments consisting of nonconforming material in the same parameters will be subject to automatic rejection and return.

3.4 In addition to the above handling of nonconforming material, the Material Review Board is the issuing authority for the Vendor Off-Specification Permit (SFD Form No. 86).

3.5 Material Review Board decisions are subject to review by S-F-D laboratories management.

STANDARD PROCEDURE INSTRUCTIONS

Title: MATERIAL CONTROL

Material Control is that function in a manufacturing organization which determines the levels and composition of inventories of materials and parts which will protect effectively the production, sales, and financial requirements of that organization. Therefore, the Material Control Department will have the following responsibilities:

1. Maintenance of inventory control records of all materials and parts - Keeping the records up to date, posting all transactions affecting them, providing data for control reports, and determining minimum quantities to be stocked at all times.
2. Receipt of all parts and materials from vendors (internal and external) - The recording and the handling of all parts and materials from the time they are received, inspected, and delivered to the stockroom.
3. Management of physical stores - To store, to safeguard, to account for all parts and materials received, and to serve the production departments efficiently.
4. Stores Distribution - The prompt filling of production requisitions for parts and materials.
5. Requisitioning of parts and materials - The writing of purchase requisitions, the securing of necessary approvals, and the delivery of requisitions to the Purchasing Department.
6. Expediting - Internal - the follow up on purchase requisitions and/or purchase orders with the Purchasing Department on required parts and material.
7. Rejection of parts and materials - The forwarding of requests for debit memos from the Purchasing Department on rejected parts and materials. Upon receipt of debit memos to see that rejected material is forwarded to the shipping department for immediate return shipment to vendor for credit or replacement.
8. Status Reports - To issue weekly usage reports, and/or any special reports re parts and materials to management and to product manager
9. Return Containers - To store and return for credit any returnable drums, bottles, boxes, etc. upon which an incoming charge has been made.

Title: MATERIAL CONTROL

10. Salvage - To collect and store all salvageable parts and materials until a decision is made to sell same. On receipt of decision, it is the responsibility of this department to have necessary papers made out and parts and materials shipped to buyer.

11. Personnel - To see that only authorized personnel are allowed in stockroom

STANDARD PROCEDURE INSTRUCTIONS

Title: IN PROCESS INSPECTION PROCEDURES

1. At various points in the manufacturing process a representative of the In-Process Control Staff performs applicable tests to determine the quality of the material being produced and to observe that the specifications are being followed.

   1.1 A number of units will be inspected either mechanically, visually, or electrically at each step in the process as outlined in the inspection specifications.

      1.1.1 This inspection will normally be performed four times a day.

      1.1.2 If at any point in any tour one piece is found defective the Process Inspector will notify the In-Process Control Engineer at the end of the tour.

      1.1.3 If two or more are found, the In-Process Control Engineer will be notified immediately.

   1.2 In the event that two or more pieces are found defective, both manufacturing and process engineering will be notified by means of Process Alert form by the In-Process Control Engineer, and corrective action will be taken.

   1.3 The In-Process Inspector will keep a record of inspection on an In-Process Control Check Sheet.

   1.4 A two hour lot will be accumulated at every position, so that if rework or further testing is necessary, it may be done with no question as to rejects being passed to the next position.

2. In-Process Control Inspection serves an additional function of inspection in certain stages of the process. Information is obtained from production dummy units to control machine adjustment feedback information.

3. For each product line copies of the daily process control inspection records are forwarded to the Chief Process Control Engineer and the Quality Assurance Manager who will evaluate the results obtained in order to compute a process average and upper and lower control limits.

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STANDARD PROCEDURE INSTRUCTIONS

Title: PURCHASING

1.0 GENERAL:

The processing of all purchase orders which are issued for the procurement of services, processes, materials, parts, components and assemblies which enter into the end product are governed by the S-F-D Laboratories General Purchasing Policies Manual. Corporate policy, procurement ground rules and Purchasing Department responsibilities are formulated within the Purchasing Policies Manual.

2.0 REFERENCE DOCUMENTS:

2.1 S-F-D General Purchasing Policies Manual, dated July 29, 1963.

2.2 SPI 1.01 Supplier Quality Program.

2.3 SPI 11.01 Quality Control.

3.0 SUPPLIER SELECTION:

3.1 S-F-D suppliers are of a select group based on demonstrated capabilities to continually deliver materials complying with S-F-D standards of quality, workmanship, reliability and value. Early in an initial negotiation with potential suppliers, a S-F-D survey team evaluates supplier facilities to ascertain its capabilities to support a S-F-D quality product. Reference Document 2.2.

3.2 S-F-D Purchase Orders delineate all of the mandatory requirements and procedures applicable to contractual requirements. Purchase Orders reference S-F-D engineering drawing specifications, characteristics and tolerances that define the parameters of the supplier item to be produced.

4.0 VENDOR APPRAISAL AND EVALUATION:

4.1 It is the responsibility of the Purchasing Department to maintain adequate vendors for supplying material and services as may be required. In order to accomplish this, the Purchasing Department must conduct both formal and informal appraisals and evaluations of reported vendor quality ratings to insure optimum quality on supplied parts and materials related to the production of tubes and other items supplied as components of the S-F-D product line.

Title: PURCHASING

4.2 The Purchasing Department will work closely with the Quality Assurance Department in determining vendor acceptability. At least once every three (3) months the vendor status should be reviewed by both departments. The following factors shall be considered in the evaluation and appraisal of vendors: Reference Document 2.3.

(a) Financial responsibility.
(b) Facilities
(c) Reputation for quality
(d) Reputation for meeting delivery schedules
(e) The vendors' own relationship with his suppliers.
(f) Ability to be competitive in pricing
(g) General relationship with S-F-D

4.3 A vendor evaluation file shall be maintained by the Purchasing Department for all major S-F-D vendors and when necessary this file shall be made available for use to other departments.

5.0 <u>PURCHASING POLICY OBJECTIVES:</u>

As stated in Reference Document 2.1 the purchasing policy objectives are:

5.1 To buy from qualified sources materials, parts, equipment, supplies and services, securing their delivery as specified at the time and place designated, and at the lowest price consistent with the requirements of quality, reliability and service.

5.2 To accomplish this with a minimum investment in materials and supplies, consistent with safety and economic advantages.

5.3 To promote and maintain good vendor relations.

5.4 To conserve the time of technical and other personnel by relieving them of the activities and time-consuming negotiations attendant to purchasing.

5.5 To furnish timely information to appropriate personnel on market conditions, supplies, prices, products and their transportation.

5.6 Through specializing and training to achieve the above objectives at less cost than would otherwise be required.

SPI: 9.01 Rev.: A

Date Eff.: 3-6-67

STANDARD PROCEDURE INSTRUCTIONS

Title: MECHANICAL GAGE INSPECTION AND CALIBRATION PROGRAM

1. Purpose:

The purpose of this procedure is to assure the adequate control of all gages used throughout S-F-D Laboratories, Inc. The frequency of gage calibration and/or certification and methods used are outlined in SPI 9.02. MIL-STD-120 is Gage Inspection used as a guide.

2. Procedure:

For each gage or other piece of mechanical test apparatus used in the division, there is prepared a "Gage Meter and Test Set Calibration Control Record" (SFD Form No. 70) maintained by the Gage Calibration Control Group of the Quality Assurance Department, located in the Incoming Material Inspection area. The following data is recorded on each card:

a. Calibration Control Number

b. Type of Gage

c. I. D. No.

d. Date Rec'd.

e. Dept. to which assigned (and person, when applicable)

f. Gage Manufacturer

g. Model and Serial No.

h. Frequency of Calibration

i. Characteristics Calibrated

j. Accuracy of Gage

k. Calibration Standards used

l. Certified Accuracy of Standard

m. Date of Calibration

n. Persons Calibrating

o. Deviations Noted

p. Corrective Action Taken

q. Return to Use Date

r. "Tickler" Index for Automatic Periodic Calibration

STANDARD PROCEDURE INSTRUCTIONS

Title: MECHANICAL GAGE CALIBRATION CONTROL

1. The following gages require certification from an approved Bureau of Standards source. Gages must be certified at least once every other year.

   1.1 Johannson Blocks

2. The following gages require calibration by an Inspector of The Gage Calibration Control Group once every thirty days, and are to be calibrated as indicated:

   2.1 To be calibrated with certified Johannson Blocks:

      2.1.1 Micrometers

      2.1.2 Vernier calipers

      2.1.3 Height gages

      2.1.4 Depth Micrometers

      2.1.5 Super Micrometers

   2.2 To be calibrated with micrometers that have been calibrated as in 2.1 above.

      2.2.1 Plug gages

   2.3 To be calibrated with plug gages that have been calibrated as in 2.2 above.

      2.3.1 Ring gages

   2.4 To be checked with wires and micrometers that have been calibrated.

      2.4.1 Plug thread gages

   2.5 To be checked with setting plugs which have been checked with calibrated wires and micrometers.

      2.5.1 Ring thread gages

Title: MECHANICAL GAGE CALIBRATION CONTROL

3. After Calibration or Use, gages are to be stored in their respective protective containers.

   3.1 All gages are to be in the custodial care of individual department heads.

   3.2 All personal measuring tools shall be inspected and serialized in accordance with this instruction.

4. Prints of all production gages and fixtures are held in the Material Inspection Department which is also the Mechanical Calibration Control area. Tool, gage and fixture calibration records are maintained in this area. The chief of MID shall be responsible for the assignment of Calibration Control numbers, execution of the sample report, inspection of assembly and acceptance test fixtures and the release to production of the aforementioned fixtures.

   The following records will be maintained in the MID Mechanical Calibration Control area.

   1. Drawings
   2. Inspection records
   3. Calibration Control Cards

Title: MECHANICAL GAGE CALIBRATION CONTROL

Guide to color code and frequency of certification on type of gage listed by numbers:

Color	Frequency	Gage Type No.
Blue	Semi-Monthly	10, 14
Red	Monthly	4, 8, 2, 9
Green	Quarterly	3, 11
Yellow	Semi-Annually	12, 5, 1, 7
Black	Yearly	6, 13

TYPE OF GAGE

1. Comparators (Optical)
2. Micrometers
3. Thread Gages
4. GO-NO-GO Gages
5. Dial Indicators
6. Gage Blocks - Shop
7. Tool Makers Microscope
8. Gages and Testers for Plating
9. Vernier Calipers
10. In-Gages
11. Vernier Height Gages
12. Torque Gages
13. Surface Plates
14. Depth Micrometers

STANDARD PROCEDURE INSTRUCTIONS

Title: ELECTRICAL TEST EQUIPMENT CALIBRATION PROGRAM

1. Purpose

This Standard Procedure has been prepared in recognition of the dependence of S-F-D Laboratories upon highly accurate and precise test measurements and reliable test equipment. These rigid measurement standards and their control are mandatory due to the nature of S-F-D Laboratories products, especially with regard to their power and performance ratings.

2. General

2.1 All electrical and electronic test equipment used in the manufacture, inspection, or testing of any product is calibrated on a routine basis by the Calibration Control Group, using certified reference standards. These reference standards are high quality precision components and instruments which are used exclusively for calibration. Reference standards never leave the calibration control area except for purposes of periodic calibration by outside calibration laboratories whose calibrating standards are traceable to the National Bureau of Standards. The reference standards are used to certify or calibrate internal transfer standards which in turn are used for individual meter calibration, except for those cases where the accuracy of the measurement to be taken requires that the measuring equipment be calibrated by means of the reference standard. This special calibration will only be done in the calibration control area.

2.2 The calibration and control of each piece of test equipment is monitored through the use of a "Gage, Meter, and Test Set Calibration Control Record", (SFD Form No. 70). These record forms are maintained by Calibration Control Center personnel in a permanent card file with an index tab "tickler" system which insures calibration at the prescribed frequency. SFD Form No. 70 specifies all pertinent identifying data on the equipment to be checked, including type of equipment, manufacturer, model number, serial number, property tag number, calibration tag number, capital test equipment number, accuracy, etc. On this card there is also found information concerning the specific calibration standards to be used in calibrating each characteristic, and their certified accuracy. At each check, space is provided for notation of deviations and any corrective action taken.

Title: ELECTRICAL TEST EQUIPMENT CALIBRATION PROGRAM

2.3 On each piece of test equipment requiring calibration there is permanently attached a calibration control number plate and a calibration tag which indicates the equipment number, department number or location, calibration frequency, calibration date, calibration expiration date, and the initials of the technician.

2.4 In addition to the above individual calibration tags, a "Test Set Control Record" (SFD Form No. 71), is mounted on all test consoles and test sets which consist of a combination of electrical, electronic, mechanical, and/or thermal measuring, indicating, or controlling equipment. This record is used as an abbreviated log for all work done on any or all parts of the console or test set, other than routine calibration noted on the individual calibration tags.

2.5 Equipment calibration frequencies are a function of the nature of the equipment, and the specific task which it performs. The frequencies of calibration vary from daily to yearly checking. In every case, however, when a piece of equipment is suspected of being out of calibration, due to mishandling, obviously erroneous indication or mensuration, the required replacement of a degraded component, or any other valid reason, the equipment is immediately recalibrated or removed from service, and substitute calibrated equipment is installed pending recalibration and/or adjustment or repair by the calibration control group.

3. Definitions

3.1 National Bureau of Standards: A chartered organization of the federal government authorized to engage in testing and providing calibration services to industry. The N.B.S. is the common reference for all technical measurements made in the United States.

3.2 Standard: A piece of equipment exhibiting an established quality or quantity of some electric, electronic, or mechanical property, or an instrument capable of measuring such a property.

3.3 Reference Standard: A standard which acts as a reference against which lower level standards are compared.

Title: ELECTRICAL TEST EQUIPMENT CALIBRATION PROGRAM

3.4 **Transfer Standard:** A standard which is employed to transfer quantitative and qualitative values from one accuracy echelon to a next lower accuracy echelon in a given measurement area.

3.5 **Test Equipment:** All general purpose equipment (standard measuring instruments); special testing equipment, including such classes as checkout equipment, acceptance equipment, inspection equipment, research and development data collection equipment; and gages and associated accessories.

3.6 **Calibration:** The process by which a standard of a given accuracy is checked against a standard of higher accuracy and adjusted as necessary to ensure that the lower accuracy standard is within the manufacturer's rated accuracy specifications.

3.7 **Certification:** The act of designating that standards and measuring and testing equipment have been calibrated and meet established requirements.

STANDARD PROCEDURE INSTRUCTIONS

Title: QUALITY CONTROL

1. General

S-F-D laboratories has adopted a quality program of advanced concept, planned and developed in consonance with S-F-D's other administrative and technical programs. This program comprises three key phases and assures the quality throughout all areas of contract performance including design, development, fabrication, processing, assembly, inspection tests, packaging, packing, shipping, storage and site installation. The three phases are Product Planning and Design, Manufacturing, Product-Quality Services.

Product Planning and Design

1.1 The product Planning and Design at S-F-D Laboratories is based upon market needs and customer preferences within existing technology and resources. The market for which each new product or innovation is aimed, is carefully evaluated and then required quality standard is ascertained. The net result is a definition of those quality standards of performance, features, and suitability, including reliability which give quality leadership in the market for which the product is planned. This definition is included in product design specifications. An important phase of S-F-D laboratories program of advanced development and improved technology is directed towards quality improvements to enable a continuation of quality leadership in each of the markets for our products.

Integrated program plans supplemented by engineering instructions are followed to assure attainment of the desired standards of quality. These standards conform to or exceed established industry and/or military requirements. In establishing a design, proper consideration is given to technological innovation, cost, and manufacturability. The plan provides for evaluation, documentation, and review of results.

Scheduling during this phase must allow adequate time for product design quality appraisal internally. Schedules must provide time for design changes to be made and evaluated, when required. Appropriate instructions, drawings, and specifications are issued to insure that product materials and processes are capable of producing a product of the desired quality.

Title: QUALITY CONTROL

Manufacturing

1.2 The manufacturing facilities will be provided and test equipment will be built or procured to the required productivity, quality standards and maintenance standards. In addition, the implementation of the quality plan will assure that the outgoing product conforms to engineering design and drawings, and meets customer requirements. The manufacturing plan shall include the following quality elements:

1.2.1 Purchases from approved sources of supply.

1.2.2 Adequate inspections and tests, or vendor certifications of materials and parts. The disposition of sub-standard material or parts shall be determined by documented procedures.

1.2.3 Sufficient in-process controls to assure compliance with engineering process instructions.

1.2.4 Procedures for the evaluation of defective material disposition of generated defectives.

1.2.5 Tests and inspection of completed devices, including production tests and quality acceptance tests, typical values, and environmental and life tests.

1.2.6 Calibration and test equipment and gage inspection procedures.

1.2.7 Feed back of sufficient data to engineering, marketing, and management to show conformance of product and processes to design specifications. This feed back will be one of the bases for design modification and process changes when necessary.

Product-Quality Services

1.3 Procedures will be maintained for field evaluation of customer satisfaction with S-F-D Laboratories products, and for determining the appropriateness of current quality standards to long-term objectives. The design, manufacturing process and quality plan may be modified as a result of customer feedback to assure customer satisfaction.

STANDARD PROCEDURE INSTRUCTIONS

Title: FINAL QUALITY INSPECTION

1. All electrical characteristic testing in final quality inspection is performed on 100% basis due to the nature and high unit value of S-F-D products. Electrical tests are conducted by a qualified test engineer and the data is recorded on the final acceptance test data sheet prepared by the Quality Control Engineer. Prior to submission, aging and pre-acceptance test data are recorded in the Test Engineer's data log book and are made part of the permanent record. The final acceptance test data sheet recording electrical test data is executed by the Test Engineer with 100% surveillance and/or audit by the Quality Control Engineer. At the conclusion of the test the inspection status of the material is indicated by a Quality Control stamp. The test data sheet is signed by the Test Engineer and by the Quality Control Engineer.

2. In the event of non-conforming product, the product is submitted to the Material Review Board for disposition which may consist of accept as is, rework, repair or scrap. In the event of MRB decision for tube opening in order to ascertain cause of failure, the Tube Reliability Analysis Review Report will be executed. Tubes which exhibit discrepancies will be put in a hold status until disposition is made by the Material Review Bo d.

3. After grouping the f tubes, a sample is withdrawn for mechanical and visual inspecti n accordance with MIL-STD-105. Mechanical and visual final acceptance inspection is performed by inspectors of the Quality Assurance Department under guidance of the Inspection Foreman. The personnel have been trained in quality control procedures and inspection accordance with the procedures of MIL-E-1. The inspection performed is dictated by customer, service agency of S-F-D specifications as applicable.

4. From the grouped lot of tubes an additional sampling may be taken for Design and Life Tests in accordance with the procedures specified in MIL-E-1 or applicable customer specifications. A product considered to be in continous production, may be sampled for design and life testing at any time in the production period.

ML-69

APPENDIX III

Ku-BAND ICEM DESIGN SUMMARY

Ku-BAND ICEM DESIGN SUMMARY

Throughout the X-band ICEM program, problems associated with the very large structure size were encountered. The large structures required were a result of a four to one scaling from existing Ka-band tube designs. Further development of the key structures, the cathode and anode assemblies, embodying designs unique to the larger X-band size, is required to provide the dimensional stability achieved in the Ka-band ICEM magnetron. By limiting the frequency scaling to a factor of two, a much more practical structure size is realized at Ku-band which should exhibit the needed dimensional stability.

A design for such a magnetron will be evolved in the following paragraphs, based upon the following requirements.

Tuning range	16.0 GHz to 17.0 GHz
Power output	300 kw (minimum)
Efficiency	40% (nominal)
Peak voltage	24 kv (nominal)
Peak current	50 amperes
Duty cycle	0.0005

1.0 CAVITY DESIGN

The starting point for the inverted coaxial magnetron design is to determine a cavity design which satisfies the specified requirements. It is required that a right-circular cavity, capable of operating in the TE_{011} mode over the specified tuning range, be found. Additionally, it is required that the TE_{011} mode be free from interference from all other cavity modes over this 16.0 GHz to 17.0 GHz tuning range. These requirements are satisfied by the cavity design which produced the mode chart illustrated in Figure 1. This cavity is 1.300" in diameter and may be seen to provide mode interference free tuning over a range of frequencies considerably greater than the

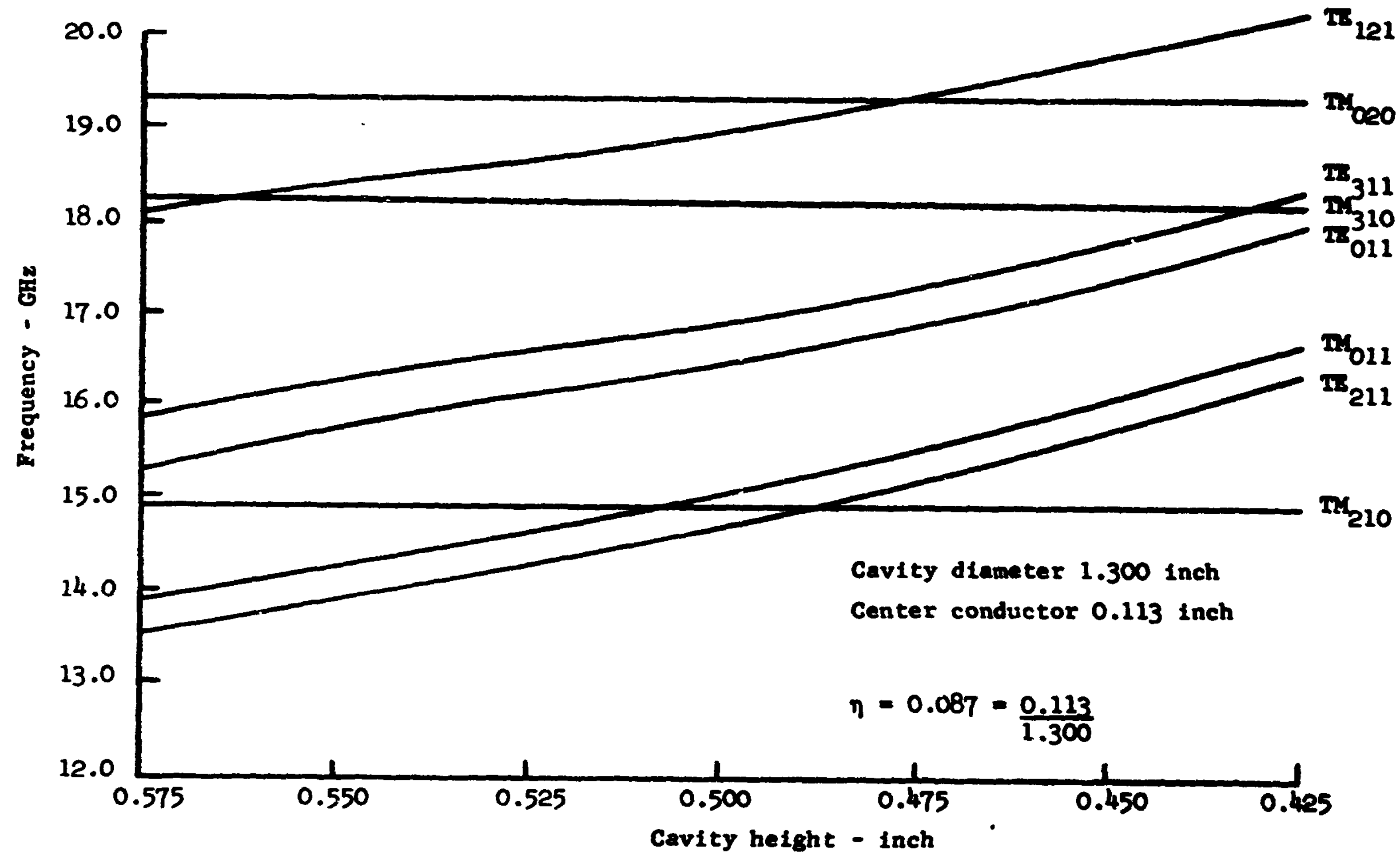


FIGURE 1 Ku-BAND ICEM MAGNETRON MODE CHART

16.0 GHz to 17.0 GHz required. Based upon hot tube performance, the rated tuning range of the tube might be extended to encompass a greater bandwidth.

The cavity mode chart, Figure 1, was calculated using equation (1)

$$\left(fD\right)^2 = \left(\frac{cr}{\pi}\right)^2 + \left(\frac{cD_c}{2L}\right)^2 \qquad (1)$$

where f = frequency
D_c = diameter of cavity
L = length of cavity
c = velocity of light
r = Bessel function root for mode of interest

The mode chart shown in Figure 1 was calculated for a coaxial cavity, having a 1.300" outer diameter with a 0.113" diameter coaxially centered inner conductor. This rod provides the means for selectively tuning the TM_{020} mode out of the desired band. All other modes of interest are influenced to a relatively small degree by the presence of the rod. Without the rod in place, the undesired TM_{020} mode would be at 16.0 GHz, which is in the required tuning range. From the mode chart of Figure 1, it is also possible to determine the approximate change in cavity length required to produce the 1 GHz tuning range. A cavity height of 0.525" places the TE_{011} mode frequency at 16.0 GHz, while a 0.466" cavity height produces a TE_{011} mode resonance at 17.0 GHz. The tuner, therefore, must provide a cavity height change of 0.059" to traverse the required band. Sufficient margin over and above a 0.059" traverse of the tuner drive must be provided in the hot tube; the traverse is readily extended to 0.100" or greater.

2.0 CIRCUIT DESIGN

Once the cavity design has been determined, the balance of the cavity-anode design is developed through electronic considerations.

To provide an overall efficiency of 40%, the electronic efficiency required in the interaction system must be 55% to 60%. This level of electronic efficiency is dependent upon the 70-75% level of circuit efficiency expected over the 16.0 GHz to 17.0 GHz cavity tuning range. An operating to synchronous voltage ratio, V/V_o, of 6.0 is required to obtain an electronic efficiency of 60%. Since the operating voltage is specified as 24 kv, the synchronous voltage must be 4 kv. The number of resonators required for a 4 kv synchronous voltage can be determined by using equation (2).

$$N = \frac{2\pi D_a f}{c\sqrt{\dfrac{V_o}{253 \times 10^3}}} \qquad (2)$$

where N = number of resonators

D_a = anode diameter

V_o = synchronous voltage

c = velocity of light

f = operating frequency

The diameter, D_a, is obtained by adding two vane lengths and two cavity wall thicknesses to the cavity diameter, D_c, already determined; i.e., D_c = 1.300". The vane length employed is equivalent to that required for a parallel-sides quarter wavelength resonator to resonate at 16.5 GHz, the center of the tuning range. This length is shortened by 10% to offset the effect of fringing capacitance from the vane tips. At 16.5 GHz, with foreshortening, a 0.160" vane length is required. Using this vane length and an 0.040" anode shell thickness, the anode diameter is determined to be 1.700". Substituting this value for D_a in equation (2), with f = 16.5 GHz and V_o = 4 kv, the number of resonators, N, required is 120.

Spacing 120 resonators around the 1.700" anode diameter, results in an 0.044" vane tip to vane tip spacing. A one-to-one metal gap-to-metal spacing produces a vane which is 0.022" thick at the anode outer diameter and 0.018" thick where it connects with the 1.380" outer cavity shell diameter. A parallel-faced cutting tool is used to form the vanes and results in the vane thickness tapering with a parallel-sided resonator.

Coupling to the cavity is provided by 60 slots cut through every other resonator pair. The slots are made equal in length to the cavity height at mid-tuning band; i.e., 0.496". Scaling from Ka-band, the slot width is determined to be 0.012".

Circuit height in this design will be 0.120". At this height, a moderate pole piece spacing is required while simultaneously holding anode power dissipation densities to safe levels. The pole piece spacing considered here should ultimately yield a minimum weight packaged tube. The gap length used at a particular level of magnetic field will directly affect the weight of the required permanent magnet. The anode dissipation level of 250 kw/in^2, which results at the specification input level, is low enough to insure a transient temperature rise at the copper vane tips that is well below the level where erosion due to copper vaporization would influence tube life.

3.0 MAGNETIC CIRCUIT DESIGN

The magnetic field requirements can now be determined from equation (3)

$$V = V_o \left(\frac{2B}{B_o} - 1 \right) \qquad (3)$$

where V = operating voltage

B = operating interaction magnetic field

B_o = characteristic magnetic field

V_o = synchronous voltage of circuit

The operating voltage is specified as 24 kv, the charactersitic or synchronous voltage is 4 kv, and the characteristic magnetic field can be derived once the cathode-to-anode interaction space has been set. Experience at Ka-band indicates that this space should be approximately equal to 85% of one circuit pitch, or 0.85(0.044) = 0.037". Since the anode diameter is 1.700", the cathode diameter becomes 1.774". The characteristic magnetic field, B_o, determined for this geometry at 16.5 GHz is 2200 gauss. By applying e equation (3), the magnetic field required in the interaction space is found to be 7700 gauss. All parameters necessary to design the permanent magnet may now be summarized. Pole piece gap length will be set to 0.240", interaction space magnetic field will be 7700 gauss, and the gap area will be 0.820 in^2. A design for the permanent magnets can be approximated from these requirements.

The length of the magnet, assuming the use of Alnico V, is derived from equation (4)

$$\ell_m = \frac{kB_g L_g}{H_d} \tag{4}$$

where ℓ_m = length of permanent magnet circuit
k = leakage factor
B_g = flux density in the gap
L_g = length of gap
H_d = magnetizing force of the magnet at maximum energy product operating point

Applying this equation with k = 1.3 and H_d = 550 oersteds for Alnico V, ℓ_m is determined to be 4.5". Equation (5) is used to determine the magnet area required.

$$A_m = \frac{B_g A_g F}{B_d} \tag{5}$$

where A_m = required area of magnet

B_g = flux density in the gap

A_g = area of gap

B_d = flux density of the magnet at maximum energy product operating point

F = leakage factor

Through the use of equation (5) with $F = 15$ and $B_d = 10{,}000$ gauss for Alnico V, the magnet area is 7.5 in^2. From the magnet length and area, the magnet volume and weight are calculated to be 34 in^3 and 9 lb, respectively. It is expected that the magnet manufacturer will be able to optimize the permanent magnet design so that the physical size and weight of the final design will be under those estimated.

4.0 HEATER-CATHODE DESIGN

The design of the heater-cathode assembly will be similar to that employed at Ka-band. The structure size resulting from this scaling should be small enough to permit the attainment of dimensional stability sufficient to insure long life.

A dispenser type emitter will be used to provide reliable operation at moderate cathode operating temperatures. The operating temperature should be attained in 5 minutes of warm-up time with 120 watts of heater power using a 20 volt heater input voltage at approximately 6 amperes of current.

Constructional details to be used are shown in Figure 2.

5.0 MODE SUPPRESSION

Two mode absorbers will be used in the design to inhibit mode competition. One absorber, placed around the cavity outer diameter in proximity to the anode cavity slots, will be used to suppress inner

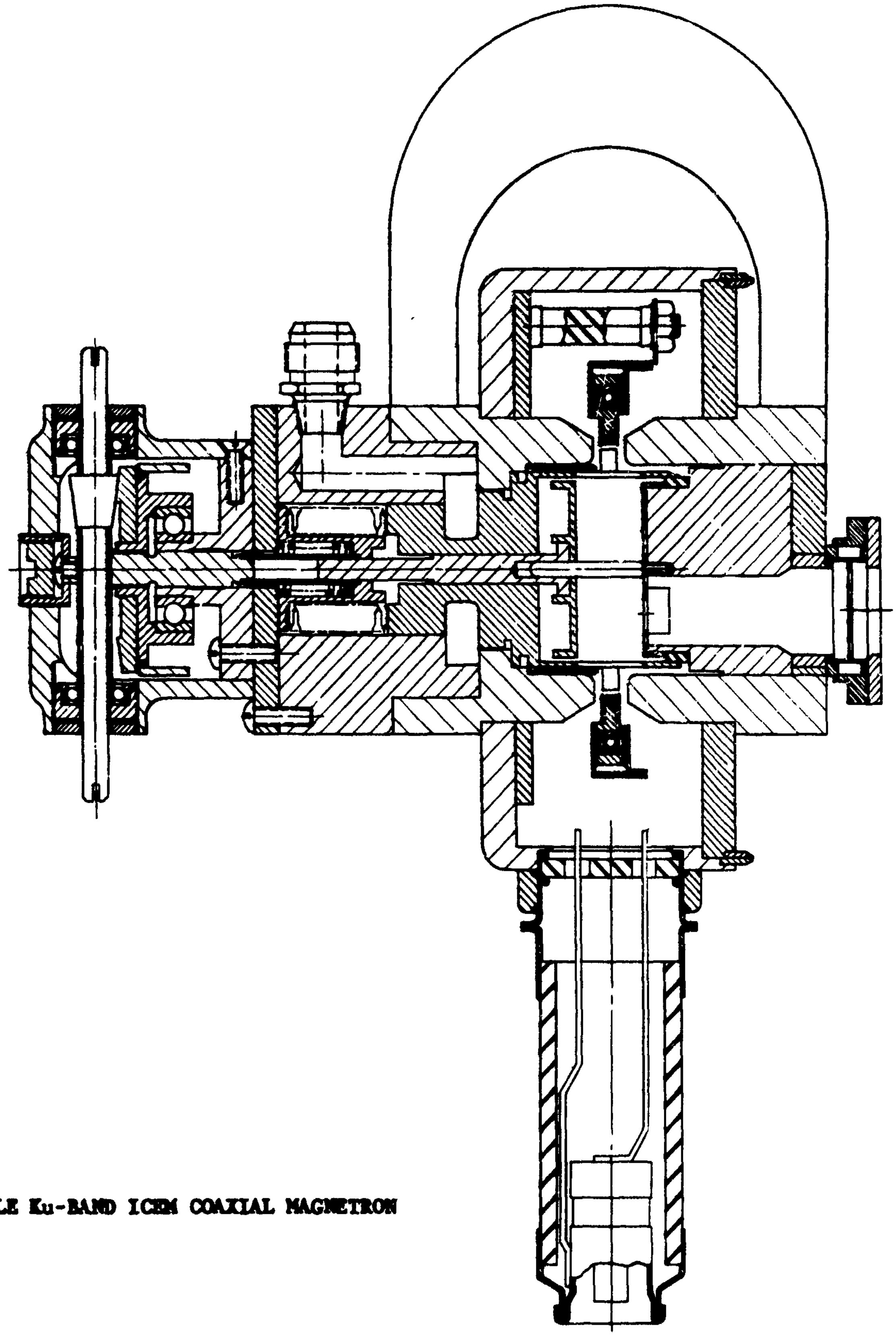
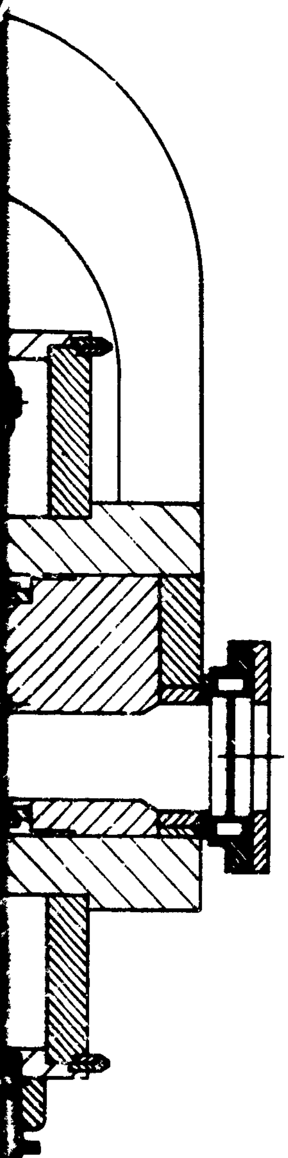
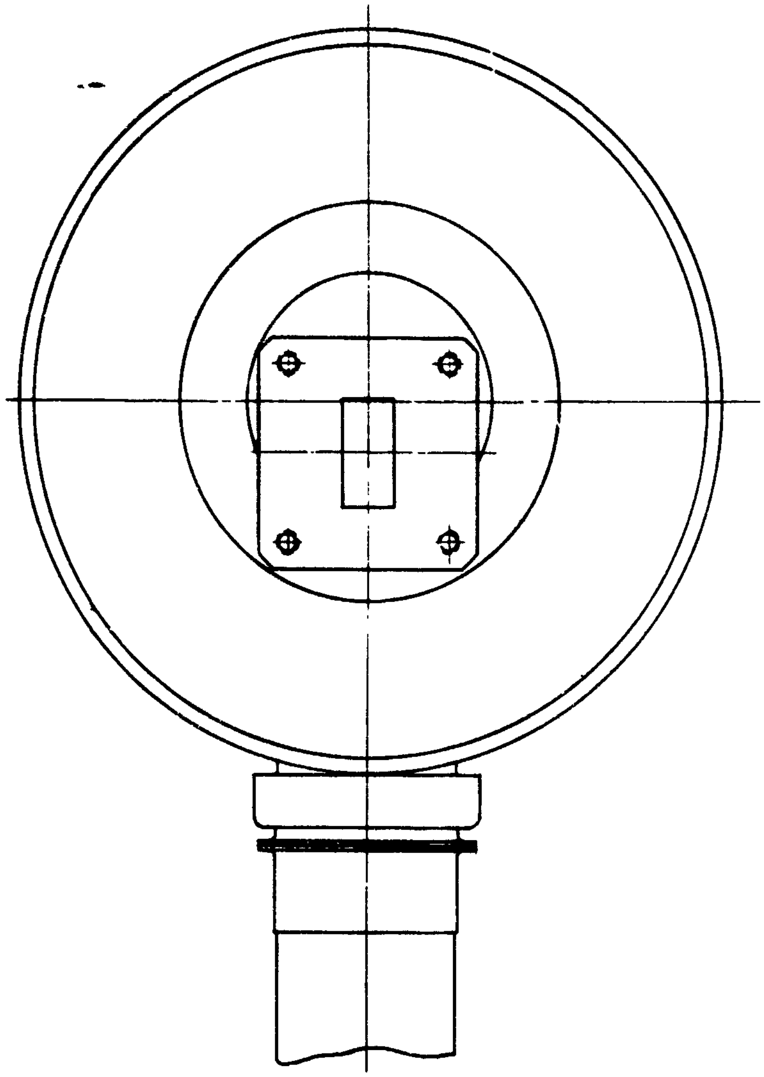


FIGURE 2 TUNABLE Ku-BAND ICEM COAXIAL MAGNETRON

A





B

circuit modes. A copper retainer which holds this absorber in place also provides heat sinking to minimize the temperature rise of this absorber under operating conditions.

A second absorber placed in a groove at the outer diameter of the cavity will suppress all cavity modes other than the TE_{011} mode. This absorber is required since the output system used will only couple the TE_{011} mode to the output load system. This method of mode suppression was proven in the X-band ICEM program.

Placement of the absorbers is shown on Figure 2, the layout of the Ku-band ICEM magnetron.

6.0 OUTPUT SYSTEM

Power output from the tube will be available directly in RG-91/U waveguide by connection to a modified UG-419/U cover flange.

The output window will be a ceramic pill-box type which will require pressurization. It is estimated that a gauge pressure of 25 psi will be sufficient to protect the window from breakdown at the 300 kw to 400 kw level.

7.0 COOLING REQUIREMENTS

At the input levels specified, approximately 360 watts of average power must be dissipated as heat. Liquid cooling would be the most efficient method of removing this quantity of heat and is indicated on the outline drawing, Figure 2. A flow rate of 0.5 gal/min of water will provide sufficient cooling.

At lower levels of dissipation, it would be possible to provide an air cooled version of the design by utilizing fins to extract heat. Such a design would be practical for operation at 20 kv peak at 20 amperes peak with a 0.001 duty cycle. At this level of input with 120-150 kw of output power, the 240 watts of dissipated power could be removed by forced air cooling of a fin system.

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13. ABSTRACT

This report describes the work performed and the results obtained on a program to improve the operational performance of a basic ICEM coaxial magnetron. In addition, manufacturing methods were to be established which would allow volume manufacture of the device at reasonable costs. Minimum peak power of 500 kw at X-band, tunable over the band from 8.6 GHz to 9.6 GHz, and a life time in excess of 10,000 hours were required.

The starting point for this program was the SFD-328 ICEM coaxial magnetron. While still a laboratory test vehicle, this tube had demonstrated performance which confirmed that the objectives of this program were realistic and achievable.

The program consisted of two elements, following a basic manufacturing methods approach. Through refinement, the device progressed from the laboratory test stage to a production device. The device was then placed in a life test program.

The final device which resulted from this program is discussed together with its advantages and limitations.

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